Energy Research and Development Division
FINAL PROJECT REPORT

ENERGY INNOVATIONS SMALL GRANT PROGRAM: 2005 INDEPENDENT ASSESSMENT REPORTS

Prepared for: California Energy Commission
Prepared by: San Diego State Research Foundation

SAN DIEGO STATE UNIVERSITY
Research Foundation
Science • Service • Solutions

APRIL 2005
CEC-500-2013-036

Prepared by:

Primary Author
Rob Queen
Project Manager

San Diego State Research Foundation
5250 Campanile Drive,
San Diego, CA 92182-1858
(619) 594-1900

Contract Number: 500-98-014

Prepared for:

California Energy Commission

Raquel E. Kravitz
Program Manager

Fernando Pina
Office Manager
Energy Systems Research Office

Laurie ten Hope
Deputy Director
RESEARCH AND DEVELOPMENT DIVISION

Robert P. Oglesby
Executive Director

PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The Energy Research and Development Division strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

Energy Research and Development Division funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Energy Innovations Small Grant Program: 2005 Independent Assessment Reports is the interim report for the Energy Innovations Small Grant Program (contract number 500-98-014) conducted by San Diego State University Research Foundation. The information from this project contributes to all of theEnergy Research and Development Division's RD&D Programs.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

The California Energy Commission has been conducting the Public Interest Energy Research (PIER) program through competitive solicitations to advance science or technology in each of the seven PIER program areas to benefit California ratepayers since 1997. In addition, the Energy Commission has also funded and managed the Energy Innovations Small Grant (EISG) Program since 1998. The role of the EISG program is to advance research into new and innovative energy concepts and technologies whose feasibility is not yet sufficiently established to meet traditional research and development (R&D) funding requirements.

The Energy Innovations Small Grant (EISG) program supports early-phase development of promising new energy technology concept. This category of projects is not covered by PIER general solicitations that focus primarily on development of established concepts. Qualifying EISG projects address one of the defined PIER RD&D areas. If the feasibility of an innovative energy concept is proven through the EISG project work, then traditional R&D funding may become available to further develop the project.

Independent Assessment Reports (IARs) are written at the completion of every EISG grant project. These reports outline the objectives of the project, discuss the successes and failures, and offer recommendations for potential future work. This report presents a collection of twenty four independent assessment reports for EISG grant projects awarded during 2005.

Keywords: Ratepayer, California Energy Commission, Energy Innovations Small Grant, EISG, Independent Assessment Report, IAR, Public Interest Energy Research, PIER RD&D, electricity, natural gas, transportation, research, energy technology concepts, project, market, outcomes, conclusions, benefits

Please use the following citation for this report:

Queen, Robert. San Diego State University Research Foundation. 2005. ***Energy Innovations Small Grant Program: 2005 Independent Assessment Reports.*** California Energy Commission. Publication number: CEC-500-2013-036

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The Energy Innovations Small Grant (EISG) program is a component of the Public Interest Energy Research (PIER) Program managed by the California Energy Commission. The PIER Program benefits California electric and gas ratepayers by funding energy research, development, and demonstration (RD&D) projects that are not adequately provided for by the competitive and regulated energy markets.

The Energy Commission recognizes the need for a program to support the early development of promising new energy technology concepts that are not mature enough to be covered by PIER general solicitations. The Energy Commission has established the EISG program to meet this need.

This report is a compilation of the Individual Assessment Reports (IARs) for grant projects that were awarded in 2005 and that have not been previously published.

All data sources for tables and figures are from the author unless otherwise noted.

CHAPTER 1
Introduction

2005 EISG Projects with IARs Included in this Section

Project	Researchers	EISG Funding
Lightweight Carbon Fiber Truss Windmill Blade Demonstrator	**M4 Engineering, Inc.**	**$74,867**
Constant Volume to VAV Conversion Technology	**Federspiel Controls, LLC**	**$75,000**
Development of Microencapsulated Phase Change Materials for Chilled Water Systems	**Infoscitex Corporation**	**$74,656**
Validation of Guthrie Lead Separation Process (GLSP)	**Bob Guthrie**	**$75000**
Energy Efficient Processing Method for Drying Fruits and Vegetables	**Zhongli Pan**	**$74,785**
Advanced Onboard Diagnostics (AOD) for HVAC Systems	**John Proctor**	**$74,778**
Solar Panel Modulation Technology: A Feasibly Study for Solar Assisted HVAC	**Strategic Development Advisors LLC**	**$74,800**
Municipal Sludge Drying and Conversion for Electricity Production	**University of Nevada, Reno**	**$74,995**
Low-Energy Desalination of Seawater	**Nrgtix, Inc.**	**$73,100**
Small Wind Turbine Generator for Low Wind Speed / Low Noise Turbines	**Sonsight Inc.**	**$75,000**
A Three-Phase Grid-Tied	**One-Cycle Control, Inc.**	**$75,000**

Project	Researchers	EISG Funding
Inverter That Suppresses Harmonics and Reactives		
Computer Controlled LED Traffic Light Power Supply Controller Time Diagnostic of Transformer Oil	**California State Polytechnic University Pomona**	**$74,026**
Nano-cable Structures for Solar Cell Application	**Q1 NanoSystems Corporation**	**$75,000**
Passively Pitchable Smart Blades for Improving Efficiency of Small Wind Turbines	**Appa Renewable Energy Systems Incorporated**	**$95,000**
Economical Two Axis Carousel Tracker for Concentrated PV Power Plants	**Green Volts, Inc.**	**$94,958**
Hydrogen Enrichment of Landfill Gas for Enhanced Combustion	**University of California, Davis**	**$95,000**
Phase Change Material (PCM) Solar Thermal Storage System	**Santa Clara University**	**$94,363**
Increasing the Energy Efficiency of Vapor Compression Systems by using "Smart" and Cost Effective Compressors	**Purdue University**	**$95,000**
Low Cost, Laser Process for Fabricating Multi-Junction Solar Cells	**Nanotron, Inc.**	**$95,000**
Nano-particle Based Catalysts for Solar Hydrogen Generation	**Frank E. Osterloh**	**$95,000**

Project	Researchers	EISG Funding
Use of Plasma Actuators to Increase Wind Energy Extraction	**Clarkson University**	**$95,000**
Prototype Energy Cell	**Primus Power Corporation**	**$95,000**
A Building Integrated Relief Damper to Improve Comfort with Evaporative Cooling	**Steven Winter Associates**	**$94,896**

CHAPTER 2
2005 Independent Assessment Reports

The Energy Innovations Small Grant (EISG) program awards numerous grants for innovative energy research projects every year. Independent Assessment Reports (IARs) highlight the project outcomes for each of the EISG projects. This chapter includes the IARs from grant projects that were awarded in 2005 that have not previously been published.

2.1 Lightweight Carbon Fiber Truss Windmill Blade Demonstrator

Awardee: M4 Engineering, Inc.

Principal Investigator: Dr. Myles Baker

2.1.1 Abstract

The goal of this project was to prove feasibility of a lightweight carbon fiber truss wind turbine blade for use on existing and future wind turbines. The innovation in this project was the use of a truss made of carbon fiber and epoxy to replace the more common fiberglass blades fabricated using a wet lay-up process. Significant weight was saved by the use of both the truss design and the material choice. To gauge the feasibility, the researchers performed material analysis and testing and full scale fatigue testing of a three bay, full scale truss section. Additional analyses included economic, weight, and scalability. Material testing proved the required strength of individual components. The researchers conducted static and fatigue testing on a three bay component. Weight calculations proved that a truss blade could have 50 to 70 percent less mass than traditional fiberglass blades. Economic analysis demonstrated that the truss design is less expensive to manufacture, ship, and assemble. Because of its lower mass, the new design allows the designer to increase the blade length for the same tower. The longer, slower blade increases power output from existing and new wind turbines without increasing tower load bearing capability.

Keywords: Truss blade design, carbon fiber, windmill, wind turbine, fatigue, graphite, wind turbine blade.

2.1.2 Introduction

The California energy problem addressed in this project was the relatively high cost of wind energy from low wind speed regions (Class IV– 5.5 to 6.0 meters/sec measured at 10 m above ground). Estimates show that using traditional blade technology to develop energy from Class IV sites results in an energy cost of approximately $0.05 to $0.07 per kilowatt hour.[1] Electricity

1 www.awea.org/faq/wwt_costs.html

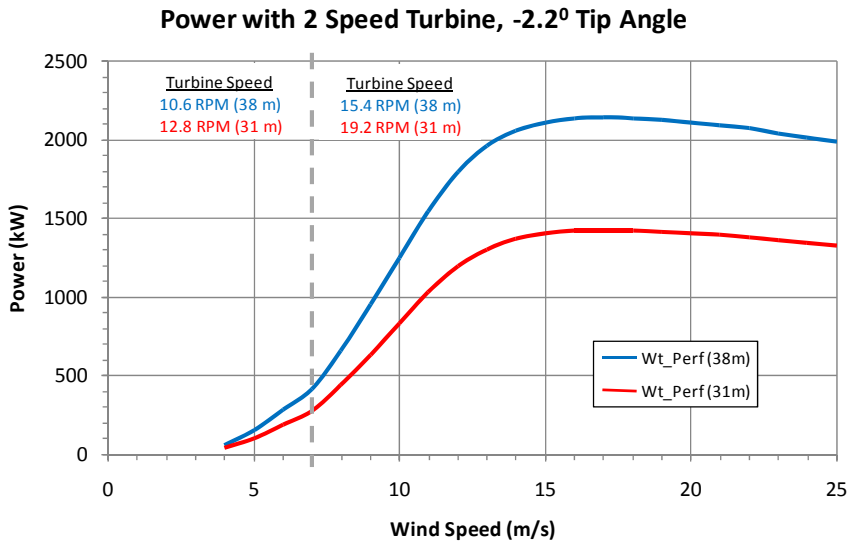
generated by natural gas fueled combined cycles costs about $0.04 to $0.045 per kWh in the same time frame.

The proposed benefits to California ratepayers included capturing wind energy from lower wind speed areas at a lower cost than has previously been achieved with conventional wind turbine technology. If the cost per kilowatt hour is reduced from the current levels of $0.05 to $0.07 per kWh to approximately $0.03 per kWh, the consumer would benefit by paying lower electrical rates while obtaining renewable energy. Investors plan to install thousands of megawatts of wind energy capacity in the next decade.

The advancement of science or technology proposed in this project was the use of a lightweight carbon fiber truss wind turbine blade to achieve a blade that is 50 to 70 percent lighter than a conventional fiberglass blade of the same length. This allows the wind turbine designer to use a blade with a radius that is 22 percent longer than conventional for a given windmill tower. The researchers confirmed that the power output scales by the ratio of the square of the blade length at a constant tip speed. The researchers calculated power output (Figure 1) after reducing turbine rotational speed for the longer blade to maintain a constant tip speed. A further increase in power may be obtained by altering the angle of attack of the blade. In Class IV wind regions the 31 m blade provides 186 kW of aerodynamic power while the 38 meter (m) blade provides 282 kW of aerodynamic power. This is a 50 percent improvement in power output. Of course the tower must be tall enough to effectively utilize the longer blade.

The researchers in this project replaced the molded fiberglass conventional blade design with a composite truss structure to carry the main bending, torsion, and shear loads. The truss was augmented with a series of ribs to define the airfoil shape, and a lightweight skin was then draped over the blade to provide a smooth continuous aerodynamic surface. The researchers constructed a three bay section of the truss blade using only a carbon fiber/epoxy composite material. While they conducted numerous tests on that section, they did not report on attaching the ribs or aerodynamic skin to the truss.

Figure 1: Aerodynamic Power vs. Wind Speed for 31 Meter and 38 Meter Rotor



The top curve in this figure illustrates the calculated performance of the 38 meter carbon fiber blade.

2.1.3 Objectives

The goal of this project was to determine the feasibility of constructing wind turbine blades using an innovative carbon composite truss structure. The researchers sought to verify that the fabrication concept, weight, and cost savings relative to conventional wet layup processes would allow construction of larger blades which could reduce the cost of energy from wind turbines. The researchers established the following project objectives:

1. Demonstrate that a carbon truss blade (three meter section) can be fabricated without a full blade mold. Confirm that acceptable airfoil shapes can be obtained through skin draping.
2. Confirm that the truss blade concept can withstand limit design loads and that fatigue properties result in acceptable life.
3. Confirm that blade diameter can be increased by at least 20 percent and that average annual energy production in Class IV wind conditions can be increased by at least 50 percent.
4. Confirm that the cost of energy can be reduced.

2.1.4 Outcomes

1. The researchers proved that a carbon fiber truss blade can be fabricated without a full blade mold by fabrication of a full scale three bay section of a truss blade. While some effort was required to accurately machine the interface areas between truss members, the assembly process was straightforward, and the test article was assembled in a few hours. The researchers did not report on draping a skin on the structure.
2. To confirm the performance of the carbon fiber epoxy material, the researchers fabricated three 12 inch by12 inch test panels (0.5, 0.75 and 1.0 inch thick). They performed compression tests to validate the performance of the resin. The test was performed on a 55 kip test frame, and the results showed a compressive strength of 52,200 Ksi for the one inch material. They then built a three bay section of a truss blade. The researchers subjected the three bay section of the truss blade to static and fatigue testing. They performed cyclic fatigue testing with no evidence of fatigue degradation of the test article.
3. The researchers showed that the blade diameter can be increased by at least 22 percent without being heavier than fiberglass blades manufactured under traditional methods. The actual diameters investigated were 31 m for the fiberglass blade and 38 m for the carbon fiber blade. In Class IV wind regions (5.5-6.0 m/s measured at 10 m above the ground), the 31 m blade provided 186 kW of aerodynamic power while the 38 m blade provided 282 kW of aerodynamic power. This was a 50 percent improvement in power output.

4. The researchers completed an economic analysis that confirmed the cost of wind energy can be reduced using this technology. They compared a 48 meter blade using traditional production techniques shipped as a single piece on the top deck of a ship to a carbon fiber truss blade of the same size shipped via 40 foot containers. The analysis indicated the cost savings delivered to the field could be as much as 30 percent.

2.1.5 Conclusions

1. The researchers met the goal of producing a full scale truss blade using carbon fiber epoxy material. They did not demonstrate the draping of the aerodynamic skin over the truss and templates.

2. Finite element models provided computer validation of the truss solution, indicating the static and fatigue strength adequate for a 20 year life on a turbine can be achieved. Static testing of components was accomplished to validate computer calculations and computed material properties of the laminate. With material properties validated and structural strength of the test article and frame validated, the researchers performed fatigue testing on a three bay structure. Only 10,000 cycles of fatigue testing were applied to the test article instead of the goal of 1,000,000. This was equivalent to testing for only 72 percent of the design stress level. If the blade were not to survive more than 10,000 cycles, it would have to be heavier and/or smaller than was claimed to achieve the goal fatigue life. The number of fatigue cycles that the blade can actually survive was not demonstrated.

3. This goal was met.

4. The economic analysis indicated a potential for lower cost of energy due to a lower cost of blade manufacture and delivery. The continued high cost of carbon fibers may have a negative effect on cost savings. The researchers did not offer details on how a truss type blade could be field assembled.

In summary, the researchers proved feasibility of a truss based wind turbine blade manufactured with carbon fiber and epoxy to reduce costs of wind generated electricity.

2.1.6 Recommendations

To effectively utilize this technology, the Program Administer recommends the following steps be taken:

1. Given the rapid rate of innovation in the wind turbine industry, determine if a competitive advantage exists for the researchers' technology.

2. Establish a working relationship with a major wind turbine manufacturer to obtain engineering requirements and compatibility information.

3. Build a complete blade.

4. Demonstrate the root section strength.

5. Demonstrate skin to rib attachments.

6. Perform long term fatigue testing on an entire blade.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.1.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. The project demonstrated the possibility of reduced cost of electricity in low wind speed areas. Wind generated electricity could be produced at a lower cost compared with the use of fiberglass technology at Class IV sites. Some sources[2] indicate reductions in the cost of electricity to be in the range of 14 to 16 percent. Benefits may increase if the availability of carbon fibers increases, forcing a large reduction in fiber cost. Currently carbon fiber technology is about eight times higher than fiberglass technology for wind turbine blades on a per pound basis. However costs could be reduced by eliminating the high capital cost of full size molds for fiberglass blades and by reducing the transportation cost of full size blades. In summary, replacing the baseline 31 m blades in this project with functionally identical 31 m truss blades resulted in a small cost reduction. The reduction in blade cost has a relatively small impact on the cost of energy. Something more is necessary to reach the target energy cost levels.

The real cost reductions are achieved by taking advantage of the fact that the composite truss blades can be made significantly lighter than the baseline blade, and a larger blade could potentially be supported by a tower of the same cost. While some redesign of the turbine components may be required, the overall cost of the wind turbine system per kilowatt hour produced should be significantly lower.

Another benefit of this project is the reduction in air emissions released during the fiberglass lay-up and curing processes in traditional blade manufacture.

California may already be benefiting from carbon fiber blade technology. The Vestas V90 line of large wind turbines already incorporates carbon fiber technology in selected components of its blades. Gamesa also incorporated carbon fiber technology in selected areas of its blades.

2 www.sandia.gov/wind/2004BladeworkshopPDFs/DaytonGriffin.pdf

However these machines do not use the truss design which is the major innovation in this project.

2.1.8 Overall Technology Transition Assessment

2.1.8.1 Marketing/Connection to the Market

By 2004 two large wind turbine manufacturers (Vestas and Gamesa) were incorporating carbon fiber technology into their blades.[3] The very high cost of carbon fibers and limited supply slowed the introduction of carbon fibers into wind turbine blades. Experts at a Sandia National Laboratory conference concluded that cost of energy reductions are limited via blade improvements alone.[4] One estimated that the introduction of carbon fibers could reduce the mass of the blades by 32 to 38 percent, while only reducing the cost by 14 to 16 percent. The truss design demonstrated in this project could limit the mass of carbon fiber required for a blade, thus reducing the cost.

2.1.8.2 Engineering/Technical

The company website does not reference any work related to carbon fiber wind turbine blades.

2.1.8.3 Legal/Contractual

The researchers had applied for one patent.

2.1.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

Should the researchers decide to go into production of wind turbine blades, they should complete a thorough environmental, safety, risk, and quality evaluation. Wind turbine blades have failed in many locations in the world leading to large liability claims.

2.1.8.5 Production Readiness/Commercialization

The researchers reported that their company could produce the blades given sufficient capital infusion.

2.2 Constant Volume to VAV Conversion Technology

Awardee: Federspiel Controls, LLC

Principal Investigator: Clifford Federspiel

2.2.1 Abstract

The goal of this project was to prove the feasibility of one component of a new system to convert constant volume heating, ventilating, and cooling (HVAC) systems to variable flow operation. The proposed system had three major components: a new control algorithm, a

3 www.compositesworld.com/articles/carbon-fiber-in-the-wind.aspx

4 ibid. Sandia

variable speed fan, and wireless sensors at each register. The fan and sensors were relatively proven technology. The goal of this project was to prove the feasibility of the control algorithm. The project leader named this algorithm the Discharge Air Regulation Technique (DART). The objectives of the project were to develop and calibrate models of DART, estimate energy savings, evaluate payback period, and evaluate the impact of system faults on the behavior of DART. The research team found that accurate calibration of the model could yield energy consumption accuracy of better than 10 percent. Energy savings and cost estimates resulted in a median simply payback period of 1.9 years for a range of factors affecting the savings and cost of converting to variable flow. The research team found that DART was sometimes, but not always, fault tolerant. Under some fault conditions DART modulated such that energy consumption was less than CAV operation while thermal comfort conditions were better than CAV operation with the same fault. However, other fault conditions caused DART to run the fan at 100 percent speed, yielding the same performance as CAV.

Keywords: Constant volume, VAV, conversion, retrofit, energy, HVAC, control systems

2.2.2 Introduction

There are three common types of constant volume heating, ventilating, and cooling (HVAC) systems that serve multiple zones: single duct systems with terminal reheat, dual duct systems, and multi zone systems. Single duct systems deliver cooled air to each zone then reheat it as needed to keep the zone space temperature close to the desired temperature. Dual duct systems supply heated and cooled air to each zone and mix the two to maintain the space temperature. Multi zone systems are a special case of a dual duct system where the mixing dampers are part of the air handling unit rather than located at each zone.

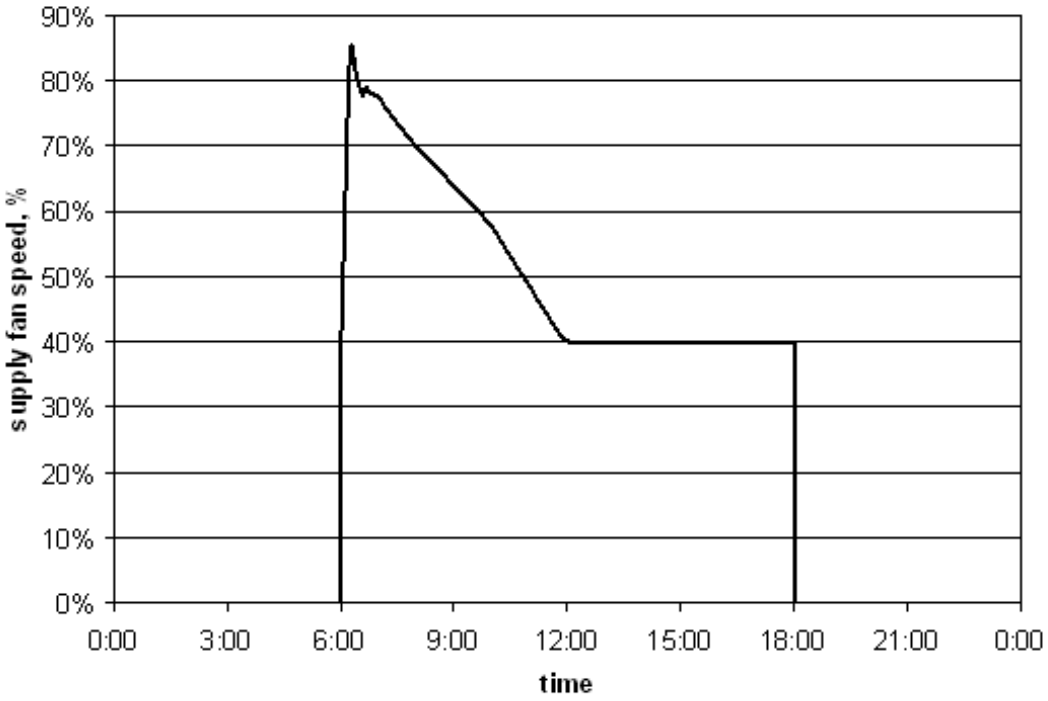
Constant volume HVAC systems described above are inefficient. In states with strict energy codes, such as California, they are prohibited in new construction. They are also prohibited by ASHRAE Standard 90.1. For HVAC systems that serve multiple zones, it is now common to use variable air volume (VAV) systems in new construction.

VAV systems have variable speed fans and terminal dampers that are controlled so the amount of simultaneous heating and cooling, or reheating, is significantly reduced. There are two common kinds of VAV systems: single duct and dual duct. Single duct VAV systems supply cooled air to each zone terminal unit, where it is metered with a control damper when cooling is required or reheated when heating is required. When heating, the amount of cooled air is reduced to a low level by the terminal control so there is much less wasted reheat energy than a single duct constant volume system. Dual duct systems deliver heated air and cooled air all the way to each zone terminal unit with separate air ducts. Dual duct VAV terminal units have independent dampers that modulate the hot airflow rate to heat a zone and modulate the cold airflow rate to cool a zone. Unlike the dual duct constant volume system, the dual duct VAV system does very little mixing. Most of the time it supplies a variable amount of hot air when heating and a variable amount of cooled air when cooling. It only mixes air when the zone load is small, so that adequate ventilation air is provided.

This project evaluated the feasibility of a new control algorithm (software) for application in converting constant air volume systems to variable air volume operation. Its planned use was in

conjunction with wireless sensors, variable speed fans, and damper controls, which have been tested prior to this project. Figure 2 shows the effect of the proposed control system on fan speed on a design heating day in Sacramento. Energy savings result from the lower fan speeds.

Figure 2: Fan Speeds for Reheat System with DART on Design Heating Day in Sacramento



2.2.3 Objectives

The goal of this project was to determine the feasibility of a new control algorithm for cost effectively converting constant volume heating, ventilating, and air conditioning (HVAC) systems to variable flow operation. The name chosen by the principal investigator was Discharge Air Regulation Technique (DART). The researchers established the following project objectives:

1. Demonstrate that the energy model of the control algorithm (DART) predicts measured consumption within 10 percent.
2. Demonstrate that the Matlab (a commercial software package) model has the same response time as the monitored system.
3. Demonstrate a simple payback of two years or less.
4. Demonstrate stable operation with overshoot of 20 percent or less.

5. Demonstrate that mechanical faults and/or network communication faults do not cause DART to set the fan speed to the minimum speed or to the maximum speed when fault free operation would result in an intermediate speed.

6. Demonstrate that faults do not cause temperatures to move outside the ASHRAE comfort zone in zones that do not have a fault.

2.2.4 Outcomes

1. Energy consumption estimates were within plus or minus 10 percent accuracy when the models were properly designed and calibrated. The research team was able to estimate fan power with a mean relative error of 2.1 percent and to estimate reheat energy consumption with a mean relative error of 8.8 percent.

2. Predicted start-stop transients were comparable to the measured transients. The measured data showed a fast thermal response to a fan startup and slower response to a fan shutdown. Virtual HVAC predicted these behaviors. Virtual HVAC was the name of a modeling program developed by the principal investigator. It worked with the MatLab program. The research team used Virtual VAC in an emulator configuration to test a pilot DART system that was to be installed in March 2007.

3. The estimated payback period was approximately two years. The estimated payback period was less than one year for larger systems with extended operating hours (e.g. 5000 hrs/yr), which are common on college campuses. The research team developed a spreadsheet calculator that can be used to quickly estimate annual savings.

4. This project showed DART to be stable, with overshoot of less than 20 percent. DART was designed to produce stable operation even when some of the building's HVAC control loops, such as zone thermostats or the air side economizer loop, are oscillatory.

5. Faults may or may not affect fan speed and energy consumption. The research team showed one example where a fault caused energy consumption to increase but to remain below the consumption level of a constant air volume (CAV) system and another example where a fault caused DART energy consumption to equal that of CAV operation (100 percent fan speed).

6. Faults may or may not affect thermal comfort. The research team showed one example where DART kept the temperature excursion resulting from a fault below the excursion that would result from CAV operation and another example where a fault caused the same temperature excursion as CAV operation.

2.2.5 Conclusions

The researchers demonstrated the feasibility of the Discharge Air Regulation Technique (DART) algorithm to convert constant volume heating, ventilating, and air-conditioning (HVAC) systems to variable flow operation. The researchers used computer modeling of fan performance, upset/fault conditions, stable temperature regulation, and economic performance to prove feasibility. The project successfully demonstrated these parameters within pre-established criteria. There were no physical measurements or testing of the entire system in this

project. The principal investigator planned to provide the DART system to a demonstration project in 2007.

2.2.6 Recommendations

The researchers should develop an approved and simplified energy calculation method for DART that can be used to determine rebates for energy efficiency programs and to enable private financing of retrofits. The research team was working with PG&E to develop such a method/tool for their energy efficiency rebate efforts. The research team also needs to investigate why Virtual HVAC does not predict oscillatory zone controls even with short proportional bands. The researchers should develop diagnostics and commissioning tools that will help avoid problems with mechanical system faults that could reduce the energy savings potential of DART and avoid cross signaling.[5] The researchers should complete a physical, side-by-side demonstration in California in a partnership with PG&E and/or SoCal Gas. Such side-by-side demonstrations are important to verify the modeled energy savings, performance, and comfort obtained as well as economic reality within the somewhat unique California building and climate conditions.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.2.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is from increased affordability of electricity in California. If the DART system, with the proven control algorithm, is successfully developed and deployed the energy, cost, and pollution savings for California could be

5 There are two types of communication fault that may occur with wireless systems: “no signal” and “wrong signal” or a signal from a different sensor/controller. The researchers evaluated the impact of communication faults, but it is unclear which of the two types of faults were evaluated.

substantial. There are more than six billion square feet of commercial floor space in California,[6] of which approximately 320 million square feet[7] are served by multiple zone constant volume systems that could be retrofitted with DART. If all were retrofitted with DART, the cost savings to California could be more than $230 million per year, the electric energy savings could be one trillion kWh/year, and the gas savings would be 100 million therms/yr. The energy savings could result in an annual reduction in carbon emissions of 165,000 metric tons. The critical issue is whether or not this technology will be deployed in the marketplace at a significant penetration level to realize a major portion of those benefits. Most commercial buildings are not owner occupied. The owner has little incentive to improve building systems because the occupant usually pays the utility bills. The occupant does not want to improve the owner's building. The savings per year are relatively small per square foot. To benefit California and the ratepayers, the principal investigator must team with energy service companies, utilities, and HVAC companies to accelerate the deployment. Utility incentives could make the retrofit mostly painless. Energy service companies could be marketing agents for the DART system.

2.2.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.2.8.1 Marketing/Connection to the Market

The research team has published two articles on the subject technology. They had commitments from Pacific Gas and Electric and Southern California Gas for subsequent funding. In addition, the researchers have partnered with two energy efficiency consulting firms, a performance contracting company, and PG&E.

2.2.8.2 Engineering/Technical

The researchers should develop an approved and simplified energy calculation method for DART that can be used to determine rebates for energy efficiency programs and to enable private financing of retrofits. The research team is currently working with PG&E to develop such a method/tool for their energy efficiency rebate efforts. The research team also needs to investigate why Virtual HVAC does not predict oscillatory zone controls even with short proportional bands. The researchers should develop diagnostics and commissioning tools that will help avoid problems with mechanical system faults that could reduce the energy savings potential of DART and avoid cross signaling.[8] The researchers should complete a physical, side-by-side demonstration in California, which was planned in a partnership with PG&E and/or

6 Rohrer, R., 2000, "California Energy Demand 2000 – 2010," CEC report P200-00-002.

7 Boedecker, E., 2005, Statistician, Energy Information Agency, U.S. Department of Energy, personal communication with the principal investigator

8 There are three types of communication fault that may occur with wireless systems: "no signal" or "wrong signal" or a signal from a different sensor/controller. The researchers evaluated the impact of communication faults, but it is unclear which of the three types of faults were evaluated.

SoCal Gas. Such a side-by-side demonstration is important to verify in real life the modeled energy savings, performance, and comfort obtained as well as economic reality within the somewhat unique California building and climate conditions.

2.2.8.3 Legal/Contractual

The researchers applied for, but had not yet received, patents on the technology at the time of this report.

2.2.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

There are no known or anticipated environmental or safety risks associated with this technology. There is a small possibility of cross signaling between adjacent devices and/or buildings that should be investigated, and protected against, to ensure customer satisfaction with the technology in installations.

2.2.8.5 Production Readiness/Commercialization

The product is ready for commercialization, beginning with the commercial demonstrations noted above, in conjunction with PG&E and efficiency firms.

2.3 Development of Microencapsulated Phase Change Materials for Chilled Water Systems

Awardee: Infoscitex Corporation

Principal Investigator: Robert Kovar

2.3.1 Abstract

Chilled water systems for space cooling in large buildings represent a major use of electrical power. These systems range in size from 100 to 5000 tons of cooling capacity (one ton of cooling is equivalent to 12,000 British thermal unit hours). The electric efficiency of the refrigeration cycle ranges from 0.6 to 1 kW per ton. The 0.6 kW per ton value is achieved by large centrifugal compressor systems (greater than 500 tons) and the 1 kW per ton value is achieved with smaller reciprocating compressor units. At typical operating conditions the water flow rate for a chiller system is approximately two gallons per minute per ton (gpm/ton) or total flow rates from 200 to 10,000 gallons per minute (gpm). Power required for pumping chilled water is typically 0.11 kW per ton.

In this project the researchers investigated the benefits of incorporating microencapsulated phase change materials (MPCM) into chilled water systems. Anticipated benefits of this technology were reduction in the flow of chilled water and pumping power, increase in the cooling capacity at the air coils, and higher refrigeration efficiency at the chiller. The researchers investigated two types of MPCM. They anticipated a 60 percent gain in the apparent specific

heat of the water-MPCM slurry when compared with water alone. Experimental results fell far short of that objective.

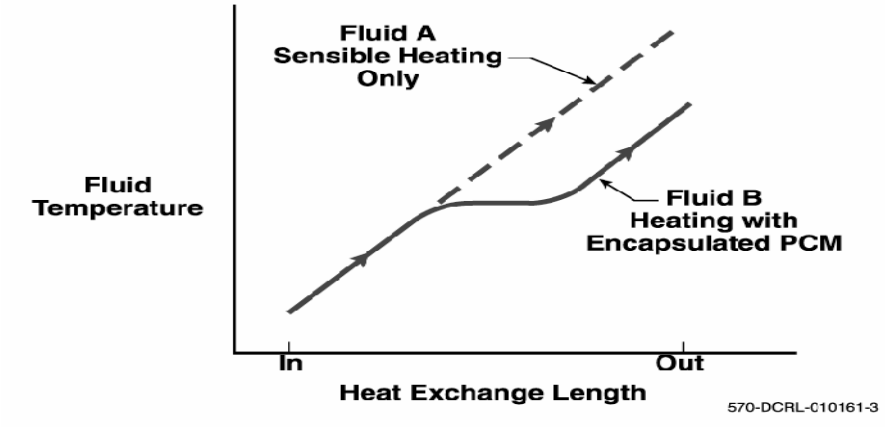
Keywords: Chilled water cooling system, cooling efficiency, microencapsulated phase change materials, energy conservation, specific heat

2.3.2 Introduction

Chilled water systems for space cooling in large buildings represent a major use of electrical power. These systems range in size from 100 to 5000 tons of cooling capacity. At typical operating conditions the water flow rate for a chiller system is approximately two gallons per minute (gpm) per ton of cooling, which suggests that total system flow rates will range from 200 to 10,000 gpm. Power required for pumping chilled water is typically 0.11 kW per ton of cooling capacity. Improving the heat transfer capability of circulating water should reduce the total amount of pumping energy required for a given amount of cooling and improve overall system efficiency.

The researchers projected the addition of microencapsulated phase change materials (MPCM) to chilled water systems used for building space cooling would result in savings of 17 percent to 20 percent in electric energy consumption. Figure 3 illustrates the impact of MPCM on the typical temperature profile of a fluid in a heat exchanger. The fluid without MPCM follows path A where the slope of the line is the specific heat of the fluid. If a phase change material is added to the fluid, the overall rate of change of temperature seen in a heat exchanger is reduced when the melt point temperature of the material is reached (path B). This addition of heat with little temperature change is due to the latent heat of fusion that must be supplied to the phase change material as it melts. Comparison of the heating curves shows that greater heat is added to the fluid phase change slurry to achieve the same temperature rise.

Figure 3: Impact of Encapsulated PCM on the Apparent Specific heat of a Heat Transport Fluid



In this project researchers investigated the benefits of incorporating microencapsulated phase change materials (MPCM) into chilled water systems to increase the heat capacity and reduce

circulating water requirements. Anticipated benefits of this technology were reduction in the flow of chilled water and pumping power, increase in the cooling capacity at the air coils, and higher refrigeration efficiency at the chiller.

2.3.3 Objectives

The goal of this project was to test the feasibility of microencapsulated phase change materials (MPCM) into chilled water systems to increase the apparent specific heat of the chilled water. The researchers established the following objectives:

1. Identify three to five nucleating and neutral buoyancy agents that would allow the use of smaller microcapsules.
2. Fabricate three to five test batches incorporating the nucleating agents.
3. Measure capsule size distribution, wax content, and differential scanning calorimetry (DSC) profile.
4. Measure the specific heat of each batch in water slurry at 10 percent solids concentration. Develop MPCM slurries that show an apparent specific heat of at least 1.6 Btu/lb-^{o}F.
5. Perform design optimization for the use of MPCM slurries in chiller systems. Prepare a system design that will reduce chiller system energy consumption by 17 percent to 20 percent.

2.3.4 Outcomes

This project resulted in the following outcomes:

1. The researchers produced several batches of MPCM to assess the effect of loading on buoyancy of the MPCM particles in suspension. They used paraffin waxes as the phase change material, with a urethane encapsulant. The researchers tested fumed silica and tungsten carbide as density compensating fillers in the capsules.
2. The researchers fabricated three test batches for use in the test chiller rig. They produced a 200 gram (g) batch of the MPCM having the best silica loading. They produced another 200 g batch having the best tungsten carbide loading. They produced another 400 g batch of tungsten carbide-filled capsules. The researchers met this objective.
3. The researchers characterized all material produced for size, wax content, and differential scanning calorimetry (DSC) profile. They met this objective.
4. The researchers measured specific heat using a test chiller rig. The results demonstrated a maximum specific heat of 1.09 Btu/lb-^{o}F, compared to the objective of 1.6. The researchers did not meet this objective.
5. The researchers performed a design analysis. However, due to the poor results achieved for specific heat modification, design of a system that would reduce system energy consumption by the targeted 17 percent to 20 percent was not achievable for the materials developed. The researchers did not meet this objective.

2.3.5 Conclusions

The researchers did not demonstrate feasibility of the proposed concept. They had forecast a 60 percent improvement in the specific heat of the cooling media. The measured increase in apparent specific heat was at best only a few percent. Additional conclusions from this project included:

1. The buoyancy of microcapsules containing phase change materials can be altered through incorporation of fillers. Proper selection of the filler enables achievement of the desired buoyancy without substantially offsetting the impact of the phase change materials on the thermal properties of the slurry.
2. Silica is not a good filler candidate due to the large volume required to achieve the desired density.
3. Tungsten carbide containing microcapsules shows promise toward meeting the required combination of buoyancy and heat capacity.
4. Obtaining adequate specific heat modification will require additional work.

2.3.6 Recommendations

Subsequent stages of the research and development of this technology should focus on refinement of the MPCM formulation and processes for its production. The primary focus should be on identifying formulations that achieve significant apparent specific heat increase. The researchers demonstrated the merits of incorporating tungsten carbide to modulate buoyancy, but further work may be required to optimize the formulation. Various loadings of tungsten carbide should be investigated and larger batches should be run on the test rig. In addition, the Program Administrator recommends refinement of the microencapsulation process to improve yield and quality of the capsules. Researchers should perform a durability test of the capsules under pumping conditions. Another test should investigate induced erosion of piping networks and seals. If capsules break down during pumping, tungsten carbide filler, a very erosive material, would be released into the circulating water, potentially causing pipe and seal breakdown. Further, the tendency of MPCM capsules to adhere to piping should be measured, as that will affect both heat transfer and apparent specific heat. Finally, the energy consumption due to the increased viscosity of circulating water/MPCM mixtures should be measured and used in system performance analyses. No field tests should be initiated until these issues have been resolved in the laboratory. Only then should field tests in real chiller systems be performed to collect data to illustrate the merits of using MPCM slurries to improve energy efficiency of chillers.

In future laboratory testing, the researchers' performance measures and calculations should be enhanced. In this project they focused only on the change in apparent heat capacity of the water/phase change material slurry. While this is the major element of the proposed system, it is not the complete story. The viscosity of the slurry will undoubtedly change, affecting the pumping power. Also, the actual heat transfer coefficients of the slurries may change.

The researchers should analyze the cost of the proposed system. The analysis should include the cost of the added materials, the manufacturing process to insert them into the system, added

maintenance or inspection costs, and any added instrumentation. The cost analysis can then be a part of an overall product lifecycle cost analysis.

2.3.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. Reducing energy consumption for space conditioning can have a significant effect on customer bills. In addition, reduced energy consumption has a direct affect on fuels consumption and emissions of pollutants and greenhouse gas emissions.

Since the project did not result in the attainment of the overall objective of a marked increase in the specific heat of the heat transfer medium utilized in chilled water systems, no hard projections regarding the benefits of the technology to the State of California can be made. However if higher specific heats are obtained and pumping requirements do not appreciably increase, the potential annual energy savings from the inclusion of MPCM slurries in chiller systems in California could reach as high as 700 million kWh, assuming full market penetration. This would be an energy savings on the order of 17 percent to 20 percent for chiller system operation. The savings would accrue primarily in the commercial sector with some savings evident in high density residential areas. Because of the major changes required to the cooling system to implement this technology, it may only apply to new construction or complete system replacement. This would slow deployment of this technology if it is proven feasible.

2.3.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.3.8.1 Marketing/Connection to the Market

The researchers had not published their results by the end of this project. Doing so is likely premature until significant specific heat increases are obtained with adequate performance in other metrics (e.g. pumping requirements, durability, etc.).

2.3.8.2 Engineering/Technical

Subsequent stages of the research and development of this technology should focus on refinement of the MPCM formulation and process for its production. The Program Administrator is unaware of any additional work in this area.

2.3.8.3 Legal/Contractual

The researchers had not applied for a patent by the end of the project. It is premature to apply until feasibility has been demonstrated. The researchers performed a patent search.

2.3.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

No analysis has been reported in these areas. Quality plans should include consideration of the durability and capsule adherence issues noted above. Safety and environmental risk analysis should focus on the breakdown of the microspheres and the release of the tungsten carbide into the cooling system.

2.3.8.5 Production Readiness/Commercialization

The product is not ready for commercialization until the issues noted above for specific heat and associated formulation characteristics are resolved. A commercial partner could be helpful in setting the research agenda to ensure that commercialization goals are met.

2.4 Validation of Guthrie Lead Separation Process (GLSP)

Awardee: Bob Guthrie

Principal Investigator: Bob Guthrie

2.4.1 Abstract

Current methods of lead acid battery recycling are energy intensive and environmentally risky. The purpose of this research project was to build a system, the Guthrie Lead Separator Process (GLSP), which would allow recycling of lead acid batteries with greatly reduced energy and greatly reduced environmental impact. Measurement of electricity consumption by each piece of equipment used in the GLSP indicated less than one kilowatt hour total of electricity was consumed per battery, much less than current smelter based approaches. This project proved the technical feasibility of using the energy saving GLSP to separate, recover, and recycle the materials in most types of lead acid batteries. In this process the recovered lead is in the form of granular lead dioxide (PbO_2) along with original form lead from the battery plates, rather than elemental lead in ingot form typical of smelting processes.

Keywords: Environment, battery recycling, lead acid batteries, energy saving

2.4.2 Introduction

Lead acid batteries are the workhorse of energy storage. The lead acid battery is being used extensively beyond the automotive and truck industry to start all types of engines for stationary functions, boats, golf cart type vehicles, and applications such as residential photovoltaics. It will continue to be used extensively worldwide for the foreseeable future, even with advances in other battery types like lithium ion. It is estimated that there are about 100 million lead acid batteries sold replacing an equal number that become spent. About 15 million of the total are collected in California (and some from neighboring states) and processed through the two

smelters in Southern California. Approximately 5 percent of spent batteries are not recycled, ending up in landfills or other inappropriate disposal.

Smelter based recycling of lead acid batteries is energy intensive and can produce toxic air pollution. Any combustible materials not removed before the lead cores enter the smelter are burned and exhausted into the air. This may include residual pieces of the plastic battery case, sulfuric acid mist acid, PVC insulation bags, lead sulfate, and possibly fine lead particles. The smelter process uses a large amount of energy to melt and process the batteries and it only recovers the lead and some of the polyurethane case material.

In this project the researchers developed a pilot scale mechanical separation process, called the Guthrie Lead Separator Process (GLSP). The innovation included a cold, wet, mechanical process, differing fundamentally from the hot dry melting process of smelting. In the GLSP the recovered lead is in the form of granular lead oxide (PbO_2) along with original form lead from the battery plates rather than metallic ingots as in the traditional smelting process. The researchers confirmed that the concepts, designs, equipment, and process achieved the project objectives.

2.4.3 Objectives

The goal of this project was to determine the feasibility of processing lead acid batteries for material recycling using mechanical processes. The researchers established the following objectives:

1. Construct and validate a pilot line to process multiple [five per day] batteries.
2. Determine if all the materials in a battery can be separated, recovered, and recycled.
3. Measure the electrical energy used to process a battery.
4. Demonstrate that the GLSP will reduce the energy required and the pollution generated by the current industry standard smelter process.
5. Develop design enhancements for future battery recycling systems.
6. Test the quality of the end products.

2.4.4 Outcomes

1. The researchers constructed a GLSP pilot line and demonstrated lead dioxide and other material separation for subsequent uses. They successfully processed five batteries per day for a period of three months.
2. The researchers demonstrated that the lead dioxide recovered by the GLSP was at least 90 percent pure and could pass through a number 325 screen. They successfully separated other battery construction materials.
3. The researchers measured the electricity consumption to process one battery in the GLSP process at less than 0.6 kWh total.

4. The researchers equated the energy consumption to a cost of about $ 0.10 per battery [assuming a price of $0.17/kwh]. The researchers did not directly compare the cost of heating fuel and electric power consumed per battery in the smelter process, but they estimated it to be on the order of 20 times the energy required by the GLSP per battery. The researchers tested for lead dust with a NIOSH approved, SKC, Inc., full disclosure instant wipes. Tests indicated low levels of lead at several locations near the GLSP. The researchers also tested for sulfuric acid mist and drift using pHydrion™ pH test strips. These tests did confirm acid in the batteries, in the drain trough, and in the collection drum. No acid was detected outside of the drum or plastic sheeting covering the drain trough. The researchers tested the water in the separation chamber and cascade system. They found the pH test strip to be essentially neutral with a pH of between 6.5 and 7.0.

5. The researchers did not provide a full scale design for a GLSP, nor did they provide specific design improvements. They did determine ways to enhance the process to achieve considerably more continuous production, make design enhancements for containment of acid drainage and fumes and a splash guard for the separator, maintain process controls to assure that the quality of each recovered material, and established employee training standards to assure consistent quality.

6. The researchers had laboratories test the lead dioxide for purity and grain size. The laboratory tests showed the lead dioxide recovered by the GLSP was at least 90 percent pure and 95 percent or more could pass thru a number 325 screen.

2.4.5 Conclusions

This project proved the feasibility of using the energy saving GLSP pilot line to separate, recover, and recycle all of the materials in batteries. The GLSP energy consumption of less than one kilowatt hour per battery met the technical feasibility criteria/test as proposed in the grant request. The researchers demonstrated that five batteries per day could be safely recycled using the GLSP. During one test run the researchers demonstrated that the GLSP, which had previously only been used on one battery at a time, could process five batteries at one time in the separator in about an hour.

Laboratory results from one sample tested locally and one sample tested at Hammond Lead Products Co. demonstrated the commercial quality of the lead dioxide product.

2.4.6 Recommendations

The researchers should design and validate a full scale and automated process to reduce labor intensive handling of batteries and acids, especially during the initial opening of batteries. Use of laser guided saws to accommodate differing physical sizes of batteries should be considered. Special attention should be paid to acid management, both liquid and fumes. Testing of various ages of batteries should be undertaken to understand how the process accommodates differing construction materials, configurations, and lead plate conditions (e.g. sulfonation, porosity, and surface conditions.) X-ray diffraction analysis should provide molecular structure information, which may be important for some potential buyers. Similarly, alpha particle analysis may be useful in selling recovered lead to the electronics industry. The researchers should develop a business plan, including recovered materials sale agreements.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.4.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is from reduced environmental impacts of the California electricity supply system. By reducing the environmental impact of recycling lead acid batteries, the environmental benefits of those renewable energy technologies (such as PV) that are used in conjunction with lead acid batteries are enhanced. Further, less electricity consumption would result from moving away from the smelter process for battery recycling.

Approximately 15 million batteries are recycled in California each year. The current recycling process requires approximately 30 kWh of electrical energy to smelt each battery. The product of the current process is reusable lead ingots. Current battery recycling in California requires up to 450 million kWh per year. The GLSP process uses 0.6 kWh or less per battery. Using the new process, recyclers would need only 9 million kWh per year to process all 15 million batteries. If all of the batteries in California were recycled using the GLSP process, it would eliminate the need for approximately 440 million kWh per year.

2.4.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.4.8.1 Marketing/Connection to the Market

The researchers have been in communication with several potential buyers of lead dioxide. Hammond Lead Products Co. expressed interest in the recovered products. Lead dioxide is in demand as a component for a wide variety of industrial products. Plastic scrap is a deep market, as is metallic lead.

2.4.8.2 Engineering/Technical

The researchers have been in contact with several interested parties. Those discussions probably include process improvement plans. No public information is available concerning those discussions.

2.4.8.3 Legal/Contractual

The researchers applied for and received a patent on the process.

2.4.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

The industrial handling of sulfuric acid and lead pose significant worker and public safety risks. Those risks have been dealt with in other industries. That information should be transferable to the GLSP process. The researchers should develop environmental and worker safety plans and procedures as part of developing a full scale process design and business plan. The researchers should develop in house laboratory capabilities to test recovered products to meet purchaser specifications.

2.4.8.5 Production Readiness/Commercialization

The process is ready for production scale up (to about 200 batteries per day) pending development of plans as described above.

2.5 Energy Efficient Processing Method for Drying Fruits and Vegetables

Awardee: Zhongli Pan

Principal Investigator: Zhongli Pan

2.5.1 Abstract

The food processing sector in California is the largest in the United States. It is also the third largest energy user in California.[9] Because one third of the energy used in food processing is consumed by drying processes, more energy efficient drying methods are needed. This project developed a new processing method for drying fruits and vegetables. The researchers named the process sequential infrared freeze drying (SIRFD). The objectives of the project were to determine the drying rates of strawberry and banana slices under different processing parameters of infrared (IR) drying as a pre-drying method for freeze drying; to compare the drying rates of IR drying and hot air drying; to measure the freeze-drying rates of pre-dehydrated strawberry and banana slices; to quantify the quality of strawberry and banana slices processed with different drying methods; and to determine the energy consumption and energy efficiency of SIRFD. IR drying showed significantly higher drying rates than hot air.

9 www.energy.ca.gov/2008publications/CEC-400-2008-006/CEC-400-2008-006-REV.PDF

Drying rates increased with the greater IR intensity. When the pre-dehydrated strawberries were freeze dried, the required drying time was reduced up to 42 percent compared to regular freeze drying without pre-dehydration. The strawberry slices processed with SIRFD were crispier and superior in quality compared to regular freeze dried fruit. The energy consumption during freeze drying decreased almost linearly with the decrease of the drying time. The significant time reduction of the new processing method indicated a great potential in energy saving. If this more efficient drying method saves 15 percent of the total energy over conventional drying and is used for 10 percent of the drying applications, the annual saving could be approximately three million kWh and 0.16 TBtu of natural gas, with an economic value of approximately $1.5 million. Energy savings were not achieved for banana chip drying using the SIRFD compared with freeze drying.

Keywords: Freeze drying, fruit and vegetable processing, energy, infrared drying, best practices

2.5.2 Introduction

The energy used in the dried and dehydrated food processing industry nationally consists of approximately 700 million kWh of electricity and 13 trillion Btu (TBtu) of natural gas.[10] The cost of this energy at 2008 prices (natural gas about $8 per MM Btu and electricity about $.08/kwhr) totals almost $170,000,000. This is 15 percent of the total energy used in food processing. The total California use of energy for food drying and dehydration is approximately 105 million kWh of electricity[11] and 5.25 TBtu of natural gas. While energy use is significant in food processing operations, energy efficiency has not been a priority until the past few years. Of greater concern for the food processing industry has been the quality and reliability of available power, since any interruptions in utility service can result in significant production losses and can impact product safety. The current preferred method of drying certain fruits is freeze drying. That method is approximately 10 percent energy efficient.

Developing a more efficient method of drying and dehydrating fruits and vegetables can reduce product cost, reduce the demand on California's energy system, and provide environmental benefits. If a more efficient drying method saves 15 percent of the energy over conventional drying and is used for 10 percent of the drying applications, the annual saving could be approximately three million kWh and 0.16 TBtu of natural gas, with an economic value of approximately $1.5 million.

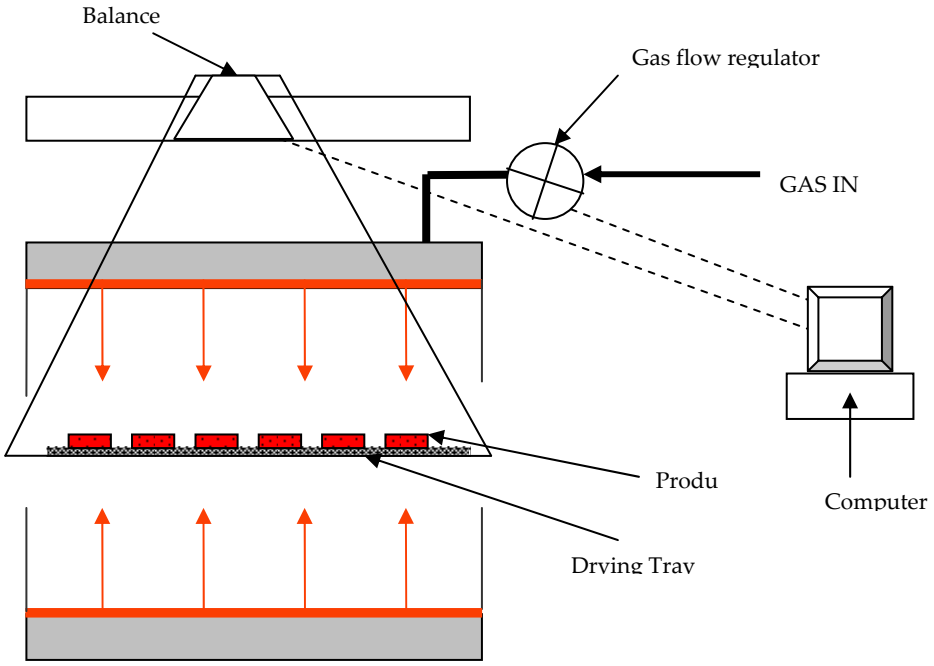
The advancement of science or technology that was proposed in this project was the use of a method of fruit drying called sequential infrared freeze drying (SIRFD) to replace freeze drying. The researchers proposed to use this method on strawberry and banana slices. Infrared drying alone has been used to dry sliced apples and onions saving up to 50 percent of the time to dry as well as energy consumed. The actual method studied in this project was intended to replace freeze drying alone as a method of drying fruits and vegetables while preserving their qualities of color, crispness, and flavor, and saving significant drying energy and time. Figure 4 shows a schematic of the infrared drying system that was tested. The researchers used an infrared

10 www.energystar.gov/ia/business/industry/Food-Guide.pdf

11 www.energy.ca.gov/2006publications/CEC-500-2006-073/CEC-2006-073.PDF

dryer/dehydrator equipped with two catalytic IR emitters powered by natural gas (Catalytic Infrared Drying Technologies LLC, KS) in this project.

Figure 4: Schematic Diagram of Catalytic Infrared Dryer (a) and Pilot Scale Dryer (b)



(a)

(b)

2.5.3 Objectives

The goal of this project was to determine the feasibility of infrared drying combined with freeze drying to dehydrate sliced fruits and vegetables while conserving quality and saving energy. The drying process used sequential infrared pre-drying followed by regular freeze drying. It was named sequential infrared freeze-drying (SIRFD). The infrared drying was used as pre-drying to remove a significant amount of water from fruits and vegetables before they were freeze dried. The researchers established the following project objectives:

1. Determine and compare the drying rates of strawberry and banana slices under different processing parameters of IR drying as a pre-drying method for freeze drying.
2. Determine and compare the freeze drying rates of pre-dehydrated strawberry and banana slices versus regular freeze drying without pre-dehydration.
3. Quantify the quality of strawberry and banana slices processed with different drying methods.
4. Determine the energy consumption and energy efficiency of SIRFD.

2.5.4 Outcomes

1. The temperature change of the strawberry slices was closely related to the IR heating intensity, as was the rate of drying. For example, with IR intensity of 5000 W/m^2 it took about 2.5 minutes for the temperature to reach about 80˚C, compared to 19.5 minutes at 3000 W/m^2. Catalytic IR drying generally reduced weight faster than did hot air drying. For example, at radiation intensity of 5000 W/m^2 it took just four minutes to reduce weight 30 percent. The same reduction took 18 minutes with hot air. The time to reduce weight increased with lowered IR radiation intensities. Compared to hot air drying, the time saving of IR drying ranged from 53.3 percent to 77.8 percent for IR intensities of 3000 W/m^2 and 5000 W/m^2, respectively.

   The heating rate of banana slices was closely related to the IR heating intensity, as was the drying rate. With radiation intensity of 5000 W/m^2, the center temperature of product reached a temperature of close to 100˚C after three minutes of heating compared to about five minutes for 4000 W/m^2.At 3000 W/m^2 the heating rate was very low. The IR heating took 3.1 and 6.2 minutes to obtain a 20 percent and 40 percent weight reduction with 5000 W/m^2 radiation intensity compared to 11.2 and 37.3 minutes for hot air drying, respectively. This was a 72.3 percent and 83.4 percent time reduction or improvement of processing efficiency for the 20 percent and 40 percent weight reduction.

2. Infrared pre-dehydration reduced freeze drying time up to 42 percent compared to regular freeze drying of strawberries without pre-dehydration (29 hours versus 50 hours). The basis for this comparison was a test using 4000 W/m^2 of IR intensity.

   Five millimeter thick bananas slices, pre-dehydrated to reduce weight 20 percent and 40 percent with 4000 W/m^2 IR intensity, were further dried using freeze drying. In these tests the banana slices dried slower during freeze drying compared to the samples without pre-dehydration. The researchers ascribed this outcome to texture changes caused by high starch content that occurred during the pre-dehydration.

3. The researchers evaluated the quality of strawberry slices dried by using either IR or hot air followed by freeze drying. The product produced with SIRFD had more desirable color, higher crispness, and more shrinkage, but a lower rehydration ratio than regular freeze drying or hot air drying followed by freeze drying. The microstructure characteristics of the dried products caused the differences in quality resulting from the different methods.

   To improve the quality and drying rate of dried banana chips, the banana slices were also treated with a dipping solution containing 1 percent ascorbic acid and 1 percent citric acid before the IR pre-dehydration. The acid dipping treatment improved the drying rate during freeze drying and effectively minimized the browning of banana chips. The researchers described the use of the dipping solution as a common food industry practice.

4. To determine the energy consumption and energy efficiency of the SIRFD method, the researchers prepared six and four millimeter thick strawberry slices. These were dried using a pilot scale IR dryer to achieve 32.4 percent and 32.1 percent weight reductions, respectively. The corresponding energy consumptions were 6202.4 kJ/kg and 7167.5 kJ/kg of water removed. Thermal energy efficiencies were 34.7 percent and 30.1 percent. This compared with freeze drying that achieved 10 percent energy efficiency. Based on the IR drying results of four millimeter strawberry slices, SIRFD could save up to 42 percent freeze drying time. The researchers estimated that the average time reduction in freeze drying of pre-dehydrated samples resulted in a 20 percent energy saving of pre-dehydrated samples compared to regular samples. When the energy consumption in pre-dehydration was counted, the overall energy saving was about 15 percent.

   Although the researchers did no drying energy calculations for banana slices, it appeared from the outcomes that no drying energy savings were possible unless an additional acid treatment was performed on the bananas.

2.5.5 Conclusions

The conclusions were different for the drying of strawberry slices compared with banana slices.

1. For the strawberry product, sequential infrared and freeze drying (SIRFD) can be used as an alternative method for producing crispy strawberry chips. IR drying had a much higher drying rate than hot air drying, and the rate increased remarkably with increases in radiation intensity. Strawberry chips dried with SIRFD had a much crisper texture and darker red color than the regular freeze dried or SHAFD products. IR pre-dehydration reduced the required time during the subsequent freeze drying process. The products from SIRFD had more shrinkage than regular freeze dried products, but less shrinkage than SHAFD products. It was estimated that 15 percent savings in drying energy could be achieved when using SIRFD compared with freeze drying alone.

2. For banana chips, the IR drying had much higher drying rate compared to the hot air drying. Its drying rate increased remarkably with the increase of the radiation intensity. The banana chips dried with SIRFD had much crisper texture and golden color appearance than the regular freeze dried products. However, the IR pre-dehydration did

not reduce the required drying time during the subsequent freeze drying process. It also resulted in more shrinkage of finished product compared to regular freeze dried products. However, the acid dipping treatment was an effective method for improving the color appearance and reducing the freeze drying time and the shrinkage. The drawback of acid dipping was reduced crispness of finished products compared to undipped products. The researchers recommended using SIRFD with the pre-dehydration to achieve less than 40 percent weight reduction and also use acid dipping treatment for producing high quality crispy product. Energy savings were not achieved for banana chip drying using the SIRFD compared with freeze drying.

In summary, the feasibility of the new drying method to save energy and improve product was proven for the strawberry slices, but not for the banana chips.

2.5.6 Recommendations

Because the test results were obtained with a pilot scale IR dryer and freeze dryer, more tests with a large scale IR dryer and freeze dryer should be conducted to verify the benefits of SIRFD at the commercial scale. The catalytic infrared dryer used in this project probably had significant side wall energy losses that had a negative effect on energy use measurements.

The tests results showed that the quality and energy saving depended on the types of fruits and vegetables. For example, the bananas required additional treatment to maintain quality when using the SIRFD. More varieties of fruits and vegetables should be tested in future studies.

Since infrared food drying is a common best practice for several fruits and vegetables, the researchers should determine the applications for the sequential infrared freeze dry method developed in this project that produce superior benefits over infrared drying alone.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.5.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is the increased affordability of electricity in California. If this technology were adopted by food processors, up to 15 percent energy saving could be achieved when drying fruits and vegetables that were formerly dried using freeze drying alone. If these savings are implemented in 10 percent of the food drying processes, the total energy saving potential in California could be about 0.16 TBtu of natural gas and over three million kWh of electricity annually.

2.5.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.5.8.1 Marketing/Connection to the Market

The researchers stated in the final report that they gained support from several food processing companies (unnamed) to demonstrate and commercialize the new processing method through corporative research projects at the Western Regional Research Center, USDA-ARS. A mobile IR processing unit was being built and would be used for demonstrating the new technology for processing various products, including crispy strawberries. The research team published two journal publications to report the results from this research.

2.5.8.2 Engineering/Technical

None

2.5.8.3 Legal/Contractual

A patent application was filed. A food processing company was interested in licensing the technology.

2.5.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

There was no indication of activity in this area.

2.5.8.5 Production Readiness/Commercialization

The researchers are considering licensing the technology. The licensee would commercialize and deploy the process. A potential licensee was developing a business plan.

2.6 Advanced Onboard Diagnostics (AOD) for HVAC Systems

Awardee: John Proctor

Principal Investigator: John Proctor

2.6.1 Abstract

Residential and small commercial air conditioning systems are generally not tested for performance and are not adjusted to ensure peak performance, even at the time of installation. The majority of these systems operate below their design efficiency due to incorrect refrigerant

charge, insufficient airflow across the evaporator coil, and other problems. Significant energy savings and electrical peak reduction could be realized by assuring that air conditioners are properly installed and maintained.

This project tested the feasibility of using an onboard air conditioner monitoring device to communicate air conditioner performance problems and their solutions to system owners, service technicians, and energy providers.

This project proved that it is feasible to use a permanently installed device to continuously monitor the performance of an air conditioner and detect problems when they occur. The device was tested in the laboratory and in the field and was proven capable of detecting common air conditioner problems.

Keywords: Air conditioner, HVAC, efficiency, fault detection, diagnostic, onboard diagnostics

2.6.2 Introduction

Air conditioning systems are a large contributor to electricity consumption in California. Air conditioning loads in the summertime are an especially important factor in peak demand and the need for adequate reserve margins to ensure against electrical system failure. Residential and small commercial air conditioning systems are generally not tested for performance and are not adjusted to ensure peak performance, even at the time of installation. The majority of these systems operate at 10-35 percent.[12] below their design efficiency due to incorrect refrigerant charge, insufficient airflow across the evaporator coil, and other problems. Significant energy savings and electrical peak reduction could be realized by assuring that air conditioners are properly installed and maintained.

Significant energy savings could be realized by:

1. Detecting air conditioner problems as soon as they occur
2. Guiding service technicians through appropriate repairs
3. Assuring repair effectiveness

This project extended Proctor Engineering Group's prior work in heating, ventilating, and air conditioning (HVAC) system energy efficiency improvement. The device tested in this project evolved from diagnostic algorithms used in the CheckMe!® program.

CheckMe!® is a computerized expert system and quality assurance program created by Proctor Engineering Group. The program guides HVAC service technicians to tune air conditioners for efficient operation. Specially trained HVAC service technicians report data from air conditioners they are servicing to the CheckMe!® call center. Operators at the call center analyze the data with the computerized expert system and guide the service technicians through appropriate adjustments and repairs. Once repairs are complete, the service technicians

12 National Energy Savings Potential from Addressing Residential HVAC Installation Problems, C. Neme, J. Proctor, and S. Nadel. Report to United States Environmental Protection Agency by American Council for and Energy Efficient Economy, February 1999

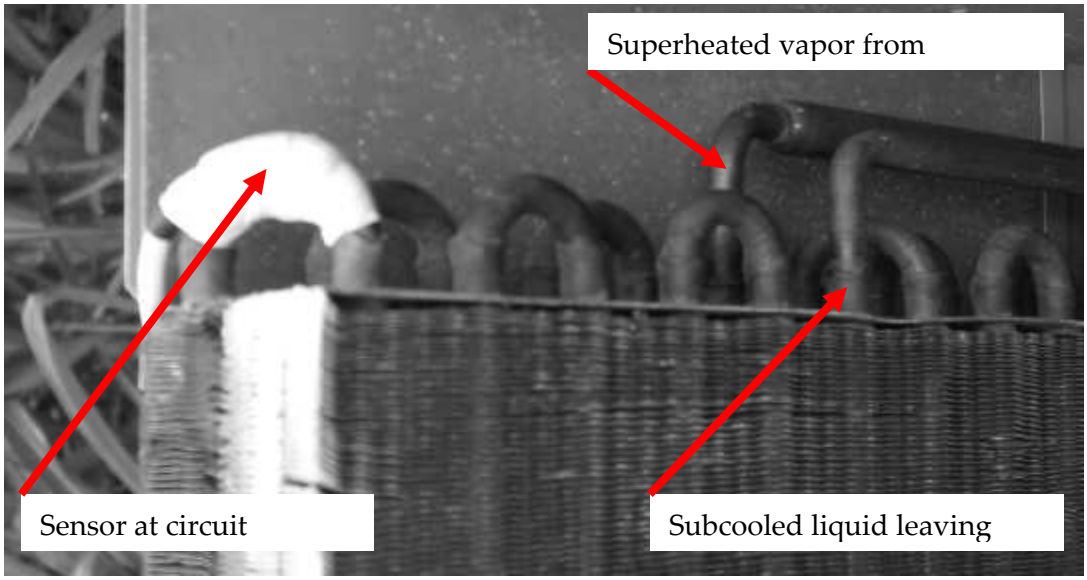
again report data to the call center for analysis and verification that the air conditioner is operating properly. Over 100,000 CheckMe!® runs have been recorded.

In 2003 Proctor Engineering Group undertook a project funded by the U.S. Department of Energy to imbed the CheckMe!® diagnostic algorithms and additional fault detection algorithms in an onboard system that operates on a real time basis. The DOE project developed an advanced onboard diagnostics (AOD) for HVAC systems. The goal of that device was to continuously monitor the performance of air conditioning systems and alert building occupants when the air conditioner needed service. Laboratory tests proved the device successful in detecting and diagnosing common air conditioner faults. No field tests were conducted.

In 2006 EISG funded research by Proctor Engineering Group to evaluate the feasibility of installing the diagnostic system on air conditioning systems in the field. The project included verification of performance in the field with air conditioners operating properly

This project tested the feasibility of using an onboard air conditioner monitoring device to communicate air conditioner performance problems and their solutions to system owners, service technicians, and energy providers. Figure 5 illustrates the location of performance related sensors in this test of onboard diagnostic systems.

Figure 5: Sensor Location for Onboard Diagnostic Systems



2.6.3 Objectives

The goal of this project was to determine the feasibility of using an onboard air conditioner monitoring device in the field to communicate performance problems and their solutions to system owners, service technicians, and energy providers. The researchers established the following project objectives:

1. Laboratory test the prototype. The prototype will successfully monitor all proposed air conditioner functions and will perform under all imposed laboratory conditions.

2. Field test prototype under fault conditions. The prototype will alert evaluator when, and only when, testing variables have a fault. Once the system is corrected, the prototype will confirm that the system is running efficiently. The prototype will perform consistently under all weather conditions and will not negatively affect air conditioner operation or efficiency.

3. Construct five diagnostic systems, each less than $400. The five will operate uniformly.

4. Locate demonstration sites. The demonstration sites will be in close proximity to lessen testing costs, chosen to show diverse conditions. Site use will be at no charge and will be available with same day notice. Sites will not be negatively affected by onboard diagnostic installation.

5. Field test onboard diagnostic systems. The systems will perform continuously and accurately to design standards. Technician interface will be easy enough for new technicians to understand and use. The diagnostic systems will demonstrate average energy savings of 17 percent or better. Results should indicate onboard diagnostic systems are ready for market.

2.6.4 Outcomes

1. Researchers constructed a prototype onboard diagnostic system and laboratory tested it at Pacific Gas & Electric and at the Proctor Engineering Group facility. Sensor readings were compared to laboratory instrumentation to prove accuracy. Two sensors were upgraded based on test results. The sensors and diagnostic algorithms proved reliable across all conditions tested.

2. Researchers conducted testing under fault conditions (under or overcharge of refrigerant, evaporator air flow, and condenser fouling) at four of the five field demonstration sites. At three sites the diagnostic system response was compared to measured capacity and efficiency loss for each types of fault. The accuracy of one onboard diagnostic system measurement was compromised due to problems installing that sensor properly in the field. Fault detection dependent upon that measurement was unreliable.

3. Researchers assembled and installed five onboard diagnostic systems in the field. At four of the sites, the air conditioners were fully instrumented to monitor performance. Installation of the sensor for refrigerant superheat proved difficult to field install properly. Measurements from that sensor were unreliable at four of the sites. With the exception of diagnostics dependant upon the problematic sensor, the diagnostic algorithms were proven reliable. Faults were not detected when none were present. The researchers reported a cost for each prototype at $378. They did not provide details of this cost number in the final report.

5. Researchers selected field test sites to include houses of various age and size and with various furnace locations. The air conditioners included units from four different

manufacturers and ranged in size from three to four tons. Air conditioning units were selected to include R-22 and R-410A units and thermostatic expansion valve (TXV) and fixed orifice refrigerant metering devices. The prototypes operated in the field from July 2006 until October 2006 without experiencing any weather related problems. There was no negative impact to the sites from on board diagnostic system installation. The researchers ran wiring along existing wires between the thermostat, furnace, and condensing unit. Sensor installation did not require any modification to the air conditioning systems.

6. Researchers tested onboard diagnostic system response to refrigerant charge, evaporator airflow, and condenser fouling faults in the field. Air conditioner efficiency loss was measured at the point each fault was detected. Results indicate the diagnostic system was capable of maintaining air conditioner efficiency at a high level. The greatest EER loss measured was 7 percent for condenser fouling. Other faults were detected at EER reduction of 5 percent or less.

Researchers detected low refrigerant charge at three of four sites. Refrigerant overcharge was not detected due to installation problems with one of the sensors. Low evaporator airflow was detected at three of four sites. At the fourth site low airflow was not detected, but onboard diagnostic fault detection was at 93 percent of the fault threshold. Researchers tested condenser fouling at one site. It was detected when the air conditioner efficiency was reduced by 7 percent.

Following fault testing each air conditioner was restored to design operation. The onboard diagnostic system confirmed the air conditioning system was running efficiently with all faults removed. At two sites evaporator airflow was low and could not be increased. The diagnostic system continued to detect a low airflow fault at those sites.

2.6.5 Conclusions

This project proved the feasibility of using a permanently installed device to continuously monitor the performance of an air conditioner and detect problems when they occur. The device was tested in the laboratory and in the field and proved capable of detecting common air conditioner problems.

The final report lacks data to support the projected product cost. It appears the prototypes contained parts estimated to cost $378. It is not clear if that number included labor, overhead, sales, installation, warranty costs, profit, etc. Even if the final cost to the consumer were under $400, the simple payback period would be 12 years for the average consumer. Most consumers do not accept products with payback periods that long.

Also, most consumers do not want a complex monitoring system that requires the use of a home computer. The system could prove worthless if it required the homeowner to log in to the system regularly to check for malfunctions.

2.6.6 Recommendations

Future work should include conducting a pilot program to install and monitor a large number (50-100) of devices in the field. Installation problems with one of the sensors should be resolved.

Hardware specifications should be developed with manufacturing partners, including fabrication and installation of the device on multiple brands and models of air conditioners. Similar efforts should focus on air conditioners typical of use in commercial buildings.

The researchers should develop and test an alert panel that provides simple information to end users indicating the need to have their system professionally inspected. The researchers should thoroughly evaluate the installed cost of the system. They should perform market research to determine the most attractive installed sales price.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding, possibly development assistance, within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.6.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research increased affordability of electricity in California. This product benefits the ratepayers in California by ensuring that air conditioners operate properly and efficiently. Proper air conditioner operation improves occupant comfort, increases the lifespan of the air conditioner, and reduces electric energy consumption. Home and business owners benefit from a lower electric bill. Energy providers benefit from reduced energy consumption and peak demand.

The majority of air conditioners operate at reduced efficiency. The estimated average efficiency improvement from giving these systems a tune-up is 17 percent. The estimated annual energy savings are 220 kWh per household with an onboard diagnostic device installed. At 2 percent market penetration into the residential new construction market, the energy savings for California are estimated at 792,000 kWh in the first year. Owner payback would be significantly better if the researchers' system were applied in hot inland valleys of California where the annual air conditioning use greatly exceeds the average. Energy savings persist for the life of

the air conditioner, since the onboard diagnostic continuously monitors the system to alert owners of any fault condition warranting service.

Higher performing air conditioners will produce less global warming than those operating with degraded performance because of the reduction in electricity consumption.

2.6.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.6.8.1 Marketing/Connection to the Market

Proctor Engineering Group has commercialized the software program CheckMe!®. Specific contractors are licensed to use this software. Imperial Irrigation District subsidizes the use of this software in their service territory. That software was not developed as part of this project. In 2008 there is no evidence that the onboard diagnostic version was available for customers.

2.6.8.2 Engineering/Technical

The Program Administrator has no evidence of further work on the onboard diagnostics system.

2.6.8.3 Legal/Contractual

The researchers had not applied for patents as a result of this project. They had not completed a professional patent search.

2.6.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

There are no known environmental or safety concerns with wide spread application of this device. As part of the commercialization of this system, quality plans should be developed to ensure consistent and accurate sensor production and installation in volume production.

2.6.8.5 Production Readiness/Commercialization

At the end of this project the onboard diagnostic system was nearly ready for production and commercialization. Results of the field test indicated that with two improvements, the system was ready to commercialize. Proctor Engineering Group reported that it was in negotiations with a major manufacturer to build and distribute the onboard diagnostic systems.

2.7 Solar Panel Modulation Technology: A Feasibly Study for Solar Assisted HVAC

Awardee: Strategic Development Advisors LLC

Principal Investigator: T. Dan Bailey

2.7.1 Abstract

This project evaluated the feasibility of using a new solar panel modulation device to enable use of solar powered air conditioning. The researchers constructed two modulators using encapsulated phase change materials (PCMs) to be used in conjunction with solar power and an adsorption chiller. They used a high temperature modulator to stabilize solar power input to the adsorption chiller as well as to provide input energy storage for off peak periods. They used a low temperature modulator to store excess refrigeration output for off peak periods. In both modulators, PCMs were encapsulated in maximum three inch diameter high density polyethylene (HDPE) spheres. For laboratory testing the researchers placed these spheres in an 18 inch section of 3 inch diameter schedule 40 galvanized pipe. The researchers selected PCMs for the high and low temperature modulators by matching PCM melting points with chiller input and output temperatures respectively.

The researchers failed to meet half of their stated project objectives and determined the project was impractical primarily due to the high cost of the solar panel arrays and the low performance of the modulators. They calculated system costs to be nearly twice the target of $4000/ton and the payback period to be more than four times the target of four years. Although the project failed to confirm the viability of the proposed technology, it did advance understanding of high and low temperature PCMs and their method of encapsulation. The researchers suggested that adoption of this technology could lead to an energy savings of 50 percent for rooftop air conditioners. However this estimate is premature and does not adequately incorporate market penetration, scope of applicability, or even the technology feasibility that this project set out to investigate.

Keywords: Renewable energy, solar, air conditioning, adsorption, phase change materials, PCM

2.7.2 Introduction

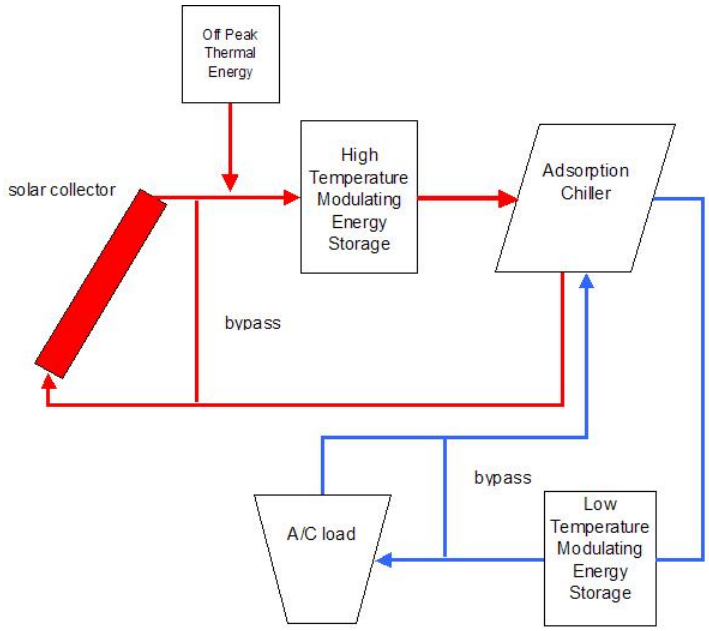
More than 28 percent of California's commercial energy usage is for air conditioning, heating, and ventilation. Air conditioning use is the single largest contributor to peak demand in the summer. At the same time, solar power generation potential is most plentiful in the summertime. Researchers in this project sought to harvest this potential in a solar assisted air conditioning system. Solar energy has had very limited application in air conditioning due to variability in energy production and lack of stability in input energy. Although solar energy generation peaks during the heat of the day, it tapers off as demand for air conditioning continues into the evening. Additionally, chillers are at their peak efficiency when operating at a given uniform temperature and will quickly become inefficient if this temperature either exceeds or falls below optimum. The technology proposed in this project was intended to expand the total hours per day that solar energy may be utilized and help California reach its renewable energy goals.

To stabilize solar input energy and introduce peak demand leveling, the researchers introduced high and low temperature modulators constructed of encapsulated phase change materials (PCMs). The high temperature modulator incorporated HS-89 with a melting point of 192°F to match the optimal input temperature of the adsorption chiller. The low temperature modulator incorporated Decanol with a melting point of 44.6°F to match the chiller output. The PCMs were

encapsulated in high density polyethylene (HDPE) spheres approximately three inches in diameter. Full scale modulators would contain numerous spheres into a tightly packed bed.

Figure 6 shows a schematic diagram of the proposed solar assisted air conditioning system. The researchers placed the high temperature modulator before the adsorption chiller to store excess solar energy, level demand, and regulate input temperature to the chiller. They placed the low temperature modulator after the adsorption chiller to store excess refrigeration capacity to be used as needed to satisfy air conditioning load requirements when chiller output decreases or demand peaks.

Figure 6: Solar Assisted Air Conditioning Schematic



2.7.3 Objectives

The goal of this project was to determine the feasibility of using a new solar panel modulation device to enable use of solar powered air conditioning. The researchers established the following project tasks and objectives:

1. Finalize high and low temperature modulator design including PCM selection and encapsulation designs, with the following characteristics:
    a. Energy storage design density of 7000 Btu/ft^3 on an installed basis for the high temperature modulator.
    b. Energy storage design density of 5000 to 5500 Btu/ft^3 for the low temperature modulator.
    c. Optimal low temperature PCM melting point in the 44°F to 50°F range.

2. Build lab scale modulator circuits and conduct modulator performance trials with the following modulator heat transfer rates:

    a. High temperature modulator = 50 to 75 Btu/hr-ft^2-°F.

    b. Low temperature modulator = 30 to 60 Btu/hr-ft^2-°F.

3. Develop an integrated mass and energy balance and carry out thermodynamic modeling of the performance of the unit. Develop case studies in three different geographic regions of the state. Achieve design electrical load of below 0.1 kW/ton of refrigeration.

4. Prepare an initial estimate of system cost and estimate likely payback scenarios for a typical commercial office building for the three geographic regions. Confirm from the project findings that the projected cost of a 300 ton air conditioning system would be less than $4000 per ton. Confirm energy savings would provide a payback of four years.

2.7.4 Outcomes

1. Laboratory testing of the encapsulated PCMs resulted in the following outcomes:

    a. Energy storage design density = 5896 Btu/ft^3 for the high temperature modulator.

    b. Energy storage design density = 5255 Btu/ft^3 for the low temperature modulator.

    The researchers presented few details of the full scale system in their report. They selected the Nishiyodo ADCM1-360 adsorption chiller to generate 300 tons of refrigeration per day. The solar array required for the full scale system would include 900 solar tubes, occupying 62,000 square feet to provide 80% of the daily load required in July. Researchers did not present details of the full scale modulator design in the report, but their calculations indicated the packed bed would include 124,502 spheres for the high temperature modulator and 183,610 spheres for the low temperature modulator. This translates to a high temperature modulator size of 12,750 gallons and a low temperature modulator size of 18,750 gallons.

2. The researchers calculated heat transfer rates as follows:

    a. High temperature modulator = 48 Btu/hr-ft^2-°F.

    b. Low temperature modulator = 40 Btu/hr-ft^2-°F.

3. Locations chosen for the case studies included Bakersfield, Fresno, and Barstow. The researchers determined the climactic difference between these locations were not significant enough to alter the projected outcomes. Consequently Bakersfield was the only case considered. In that study design, electrical load equaled 0.067 kW/ton of refrigeration.

4. The researchers' cost analysis for a 300 ton solar assisted air conditioning unit indicated projected capital costs of $7,726 and a payback period of 17 years.

2.7.5 Conclusions

1. The researchers clearly outlined the selection process for the PCMs and the encapsulating material, including various alternatives evaluated. They did not adequately evaluate alternatives for the solar collector, chiller, or modulator design. The researchers used qualitative justification in selecting the Nishiyodo chiller, with no quantitative support. They did not address other chiller alternatives in their final report, nor did they eliminate others from consideration based on technical evidence. Similar to the chiller selection, the researchers gave a broad description of available solar technologies and simply selected one without presenting the technical basis for selection. The three inch diameter size of the encapsulating sphere appeared to be chosen out of convenience for the lab testing, without any effort to conduct sensitivity studies based on sphere sizing or bed configuration. The researchers failed to address the impact of temperature cycling on either the PCMs or their encapsulating device.

    a. Although there was a discrepancy in the reported energy storage density for the high temperature modulator, neither reported value met the objectives.

    b. The researchers met the objective for energy storage design density with the low temperature modulator.

2. The researchers met the objectives for heat transfer rate for the low temperature modulator, but not for the high temperature modulator. However, it is important to note that the heat transfer rates presented in the conclusion of the report did not correlate to any of the detailed calculations presented in the body of the report. Therefore some question remains as to what rates were actually achieved. Further, the heat transfer rate calculations may have been performed incorrectly. A thorough analysis of the modulator performance should have included computer simulation studies. Although demand leveling and peak shifting were discussed in the researchers' proposal and subsequent report, they made no attempt to evaluate the effectiveness of the system in achieving either of these strategies.

3. The researchers met the objective for design electrical load. However, because the answer was stated without identifying the component loads, the result cannot be validated. The researchers selected three cities with nearly identical climactic characteristics. Two of the cities, Bakersfield and Fresno, were within the same climate zone, and Barstow was in a similar climate zone. This sample is not representative of the state as a whole and does not address case studies in any of the remaining 14 California climate zones.

4. The researchers did not meet the cost analysis objectives. The calculated capital costs were approximately twice the objective of $4000, and the payback period was more than four times the objective of four years. Calculations performed by the researchers included overly aggressive assumptions. For example, the researchers assumed that all days will be sunny and clear and that solar energy can be captured 365 days per year for 10 hours per day. The researchers estimated this technology could lead to an energy savings of 50 percent of California's annual consumption for commercial rooftop air conditioners. This translates to a savings of five billion kWh per year. This calculation

assumes 100 percent market penetration throughout the state and suggests that the technology is applicable to all climate zones, rather than limiting applicability to those represented by the restricted sample set selected for the climactic case study. Further, the 50 percent consumption savings has no technical justification. Other unrealistic assumptions include the continued availability of a 30 percent Federal tax credit to decrease the capital cost of the solar unit, neglecting annual maintenance costs, and neglecting any heating benefit that might be derived from the solar heating. The researchers acknowledged that at least some of the assumptions were overly optimistic. Undoubtedly those assumptions led to unrealistic cost estimates and overestimates of potential savings.

The investigation led by the researchers appeared to be limited and lacked the depth to establish the feasibility of the proposed technology. Nearly all details of the investigation's procedures, outcomes, alternatives, and cost analyses were omitted from the final report. Although the technical reviewers identified key benefits of the technology, the researchers were quick to abandon the proposed technology. They did not prove feasibility of this concept.

2.7.6 Recommendations

Although solar assisted air conditioning appears to have potential for cost savings and renewable energy use, additional research should concentrate on more cost effective methodologies. Future work with phase change materials should include extensive computer modeling before construction and testing of hardware.

2.7.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. The researchers estimated that the adoption of solar assisted air conditioning could results in a savings of up to 50 percent of the 11.4 billion kWh per year used for commercial rooftop air conditioning. They did not discuss in detail the basis for this estimate, and thus it could not be validated by the Program Administrator. The researchers reported high capital costs for unit installation. Until the capital costs are significantly reduced, market penetration is likely to be low. Due to the incomplete state of technology development, it is premature to attempt to assess the potential benefits of this technology.

2.7.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.7.8.1 Marketing/Connection to the Market

The researchers had not evaluated the marketability of the technology by the end of this project.

2.7.8.2 Engineering/Technical

None identified.

2.7.8.3 Legal/Contractual

The researchers performed a rudimentary patent search and did not identify any potential infringements.

2.7.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

The researchers did not prepare these plans because the technology has not been sufficiently developed.

2.7.8.5 Production Readiness/Commercialization

The researchers discontinued efforts towards commercialization until advances in solar panel technology can reduce system capital costs.

2.8 Municipal Sludge Drying and Conversion for Electricity Production

Awardee: University of Nevada, Reno

Principal Investigator: Charles J. Coronella

2.8.1 Abstract

This project evaluated the technical and economic feasibility of a new process involving the fluidized bed drying of wastewater sludge followed by thermal gasification of the dried sludge to a low energy density (low BTU) synthetic (syn) gas that could then be used to fuel an electrical generator such as a gas turbine. The motivation for such a project is the potential resource value of the high moisture content sludge. The annual energy potential in California of over 700,000 metric tons (dry basis) per year of sludge is 400 MW in terms of its fuel value and at least 135 MW when converted to electricity. The objective of the technical work performed in this project was to determine the feasibility of the fluidized bed dryer process. This included collecting data on the moisture content of as-produced sludge from three wastewater treatment plants, as well as measuring the equilibrium moisture content as a function of air temperature and relative humidity. The researchers designed, built, and tested a bench scale fluidized bed dryer for drying sludge. They used the results to design an integrated process for the

conversion of sludge to electricity. For a publicly owned mid-sized plant, a total capital investment of six million dollars is required to produce 1.4 MW (12 hours per day), and the final cost of the power is 8¢ per kWh. The discounted cash flow rate of return on the investment is 23.2 percent, for a 10 year long project.

Keywords: Wastewater sludge, biosolids, gasification, renewable energy, fluidized bed drying, equilibrium moisture content

2.8.2 Introduction

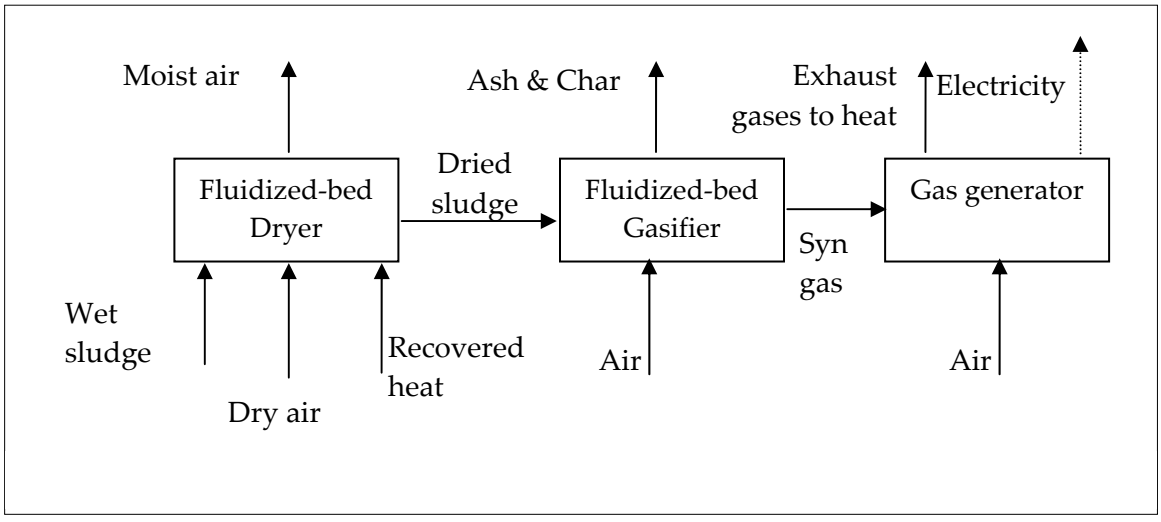
The California energy problem being addressed with this proposal is the creation of additional energy resources from the conversion of wastewater sludge into electricity. In California there are three million tons of wet sludge generated annually, a significant waste stream. This sludge has a dry matter content of 715,000 metric tons of sludge with a caloric value of 19 MJ/kg. With a power cycle efficiency of 35 percent, the potential for production of renewable power is 130 MW.

The benefits to California ratepayers lie in the potential for wastewater treatment plants to supply a significant portion of their energy from utilizing the previously wasted biomass energy in the sludge. According to the Wastewater Engineering textbook energy consumption for an activated sludge system is at least 1200 kilowatt hours per million gallons per day (MGD). According to the State Water Quality Board (SWQB) database there are 89 publicly owned activated sludge plants with capacities larger than two million gallons a day (MGD) that together treat approximately 2.5 billion gallons of wastewater a day in California. For these wastewater treatment plants, energy consumption of activated sludge systems in California is estimated to be at least 3000 megawatt hours a day (2500 times 1200 divided by 1000). The average hourly demand of 125 MW could be completely supplied by the sludge energy.

The main technical advancement proposed in this report was in the reduction of the moisture content of sludge. Sludge is usually produced with moisture content of greater than 70 percent and often as high as 85 percent. For gasification processes, fuel should have a moisture content of no more than 30 percent. The researchers developed a self-contained process for installation at wastewater treatment plants. The process had three components: drying, gasification, and electrical generation. The focus of this project was on sludge drying using a fluidized bed drying process shown in Figure 7. Figure 8 shows how this drying process fit into the overall sludge-to-energy system.

Figure 7: Test Fluidized Bed Dryer

Figure 8: Schematic of the Overall Gasification and Electrical Generation Process



2.8.3 Objectives

The goal of this project was to determine the feasibility of fluidized bed drying of wastewater sludge. The dried sludge would feed into a fluidized bed gasifier. The resulting synthetic gas

would fuel an electric generator such as a gas turbine or internal combustion reciprocating engine. The researchers established the following project objectives:

1. Establish baseline biological and chemical characterization of municipal sludge including moisture content (± 0.5 percent) and pathogenic activity.
2. Identify and analyze the equilibrium moisture content (± 0.5 percent) of sludge under typical conditions of drying, i.e. temperatures between 25 ºC and 125 ºC, and relative humidity between 0 and 100 percent.
3. Design and construct a laboratory scale fluidized bed for sludge drying with operating conditions based on the findings from Objectives 1 and 2. Optimize the operation of this drier by performing experiments while adjusting the temperature, humidity, and flows until at least 30 percent moisture content is reached.
4. Perform energetic characterization of the dried sludge product obtained from Objective 3 through calorimetric measurements to determine its heating value in MJ/kg of dry matter to verify its potential as fuel for electricity production. Test dried sludge from at least three distinct treatment plants.
5. Perform a cost analysis for the sludge drying process and confirm that sludge can be dried for less than $50 per ton dry solids.
6. Perform a scaling design analysis for the proposed technology. Establish the cost for fuel production (sludge drying) for three scales of publically owned wastewater treatment plants: small (2 MGD), medium (40 MGD), and large (500 MGD).
7. Design and synthesize a process flow sheet diagram (PFD) using the proposed technology for electricity production. The PFD will allow a conceptual comparison of this technology with competing renewable and nonrenewable technologies.
8. Perform preliminary profitability study for power generation. Confirm power can be produced in a 10 MW IGCC plant at $0.08 per kWh.

2.8.4 Outcomes

1. The researchers collected sludge samples from three regional facilities. The moisture content (MC) ranged between 76 percent and 85 percent (± 0.35 percent), with higher MCs at plants with centrifuge sludge processing and lower MCs at plants with belt filter press sludge processing. The levels of E. Coli and total coliform were quite high, 2.1E6 mpn/100 ml E. coli and 2.0E8 mpn/100 ml total coliform.
2. The researchers measured equilibrium moisture content (EMC). EMC increased with relative humidity (RH) and decreased with temperature. For RH between 10 percent and 80 percent and temperature between 30 °C and 60 °C, EMC varied between 9 percent and 33 percent.
3. The researchers constructed a three inch diameter fluidized bed with instrumentation sufficient to monitor and control the temperature and air flow. The instrumentation monitored continuously the humidity of the exhaust gas and the pressure drop of the bed. The equipment successfully dried sludge in batch mode to 30 percent moisture. At

a fluidized bed temperature of 50 °C, the sludge took almost twice the time to dry as compared with sludge bed temperatures of 70 °C to 80 °C.

4. The researchers collected sludge samples from three regional facilities and measured the heat of combustion from each. The lower heating value (LHV) of the dried sludge ranged from 16.7 MJ/kg to 23.2 MJ/kg.
5. The cost analysis of sludge drying revealed that for a plant that processes 50,000 tons/year, the installed capital costs were $1,345,000 and operating costs were $443,000 per year. For this size plant the overall cost to dry sludge to 30 percent moisture would be $52/ton (dry basis).
6. The scaling study yielded the results shown in Table 1. In only the smaller plant was the cost of sludge drying prohibitive. Drying is cost prohibitive for a plant processing less than 25,000 tons/year.

Table 1: Scaling Study

Scale Plant (MGD)	Fixed Capital ($1000)	Operating Cost ($1000/yr)	Fuel produced (tons/yr)	Cost of fuel ($/ton fuel)	Cost of disposal ($/ton sludge)
2	192	187	534	382	54
40	1,345	443	10,700	52	11
500	5,323	1,229	133,500	18	3.8

7. The researchers completed calculations to maximize heat integration. Dried sludge was sent to a gasifier, which produced fuel gas. Fuel gas was burned in a generator for production of electricity. Heat was recovered from the generator for use in the dryer. Figure 8 shows the simplified flow sheet for this process.
8. The economic study for power generation included the costs of drying gasification and electric generation. Researchers calculated a cost of electricity of $.08 per kWh. The discounted cash flow rate of return (DFCRR) was 23 percent for a medium sized wastewater plant (40 MGD) that produced 1.4 MW. For a large wastewater plant (500 MGD) the DCFRR rose to over 80 percent and produced over 17 MW of electricity.

2.8.5 Conclusions

1. Wastewater treatment derived sludge is a viable renewable fuel to produce electricity, even with high moisture content.
2. The researchers successfully measured and characterized the sludge.

3. The technical feasibility of drying sludge at low temperatures was successfully demonstrated.

4. On a dry basis, the heating value of wastewater sludge ranged between 17 MJ/kg to 23 MJ/kg. Thus, it might be considered similar to wood or sub-bituminous coal.

5. The researchers determined the cost of producing a fuel with 30 percent moisture from sludge to be more than $50/ton under certain conditions.

6. The initial moisture content of sludge should be less than 75 percent, so the drying process can operate with lower temperature air. Some waste water facilities produce sludge with a higher moisture content. Processing that sludge may require additional heat. This could be obtained through the heat integration at the wastewater plant via combustion of bio-gas produced in the anaerobic digester.

7. It is not economical to dry sludge from small waste water plants. Costs are significantly reduced as the plant size increases.

8. Solid waste disposal is significantly reduced using this process for sludge processing: about 6 percent by mass of the incoming sludge.

9. Economic evaluation suggests that power might be made available to the grid at a cost of $0.08/kWh. Further, the sensitivity of the proposed process to the market price is relatively low.

10. Profitability measures of the process, such as the discounted cash flow rate of return (DCFRR), indicate that the process is viable for plants above 40 MGD.

11. The DCFRR is quite sensitive to fixed capital expenses,, and to some extent on operating costs, as well. Reducing capital costs would achieve substantial benefits.

12. The DCFRR is quite sensitive to receiving fees in lieu of tipping fees. For any location where the cost of sludge disposal is greater than $40/ton, this process will appear quite attractive. The average cost of landfill disposal in California is approximately $40/ton, with urban locations experiencing higher rates. This indicates significant market potential for the process.

13. The feasibility of thermally converting wastewater sludge into renewable energy was proven both technically and economically.

2.8.6 Recommendations

1. The gasification of fuel produced from dried sludge must be demonstrated, at least on a small scale. Actually measuring the fuel value of the fuel gas would be invaluable. Eliminating tars, catalytically or otherwise, is absolutely essential. No process will be built until tars have been shown to cause no problems.

2. A more in-depth market survey must be undertaken. Although this report demonstrates the economic viability of the process, it is entirely a different matter to get buy in from potential customers, who consist primarily of municipally owned organizations and are risk averse.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.8.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. This project developed a process that has the potential to generate 400 MW of electricity from a renewable source, sewage sludge, and at a reasonable cost of the electricity. The technology has the added benefit of removing a waste stream from the environment. This waste stream is about three million metric tons/year in California, and represents a growing concern in many communities throughout the state.

2.8.8 Overall Technology Transition Assessment

2.8.8.1 Marketing/Connection to the Market

The researchers discussed this concept at a national meeting of the American Institute of Chemical Engineers

2.8.8.2 Engineering/Technical

The researchers are seeking funding to build a prototype gasifier.

2.8.8.3 Legal/Contractual

There will be substantial regulatory barriers to guide the development of this project, primarily related to water treatment.

2.8.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

Work should be done to determine the amount of pathogens and viruses that may be present in the residual sludge to confirm that they are destroyed during the drying and gasification processes.

2.8.8.5 Production Readiness/Commercialization

The researchers indicated they need help in formulating business and commercialization plans.

2.9 Low Energy Desalination of Seawater

Awardee: Nrgtix, Inc.

Principal Investigator: Subramanian Iyer

2.9.1 Abstract

This project investigated an alternative desalination concept to produce fresh water in a more energy efficient way than current desalination methods. The goal of this project was to determine the feasibility of using novel organic and inorganic solvents and solutes to create osmotic pressures across a semi-permeable membrane, allowing forward osmosis to take place with substantially lower energy requirements in comparison to reverse osmosis or thermal distillation processes for desalination.

After the researchers investigated many draw solutions, they selected potassium phosphate and potassium pyrophosphate as inorganic solutes. Both have high solubility in water and sufficient osmotic differentials with seawater, thus yielding high recovery of fresh water across a semi-permeable membrane. In addition, the researchers identified novel organic solute molecules as potential draw solutes. A nano-filtration process efficiently regenerated the diluted draw solutions from the forward osmosis process, yielding both fresh water and a concentrated draw solution for recycling to the forward osmosis unit process. By the end of this project, the researchers had proven a prototype seawater desalination technique which consumed much lower energy than traditional reverse osmosis processes, even though it required pressures as high as 200 psi. Further research and development work needs to be done for creating higher flux nano-filtration membranes.

With further development of nano-filtration membranes, the forward osmosis process could be beneficial for seawater desalination in California, identifying a new resource for fresh water and satisfying both economic and environmental concerns.

Keywords: Desalination, forward osmosis, nano-filtration, seawater, semi-permeable membranes, inorganic and organic solutes

2.9.2 Introduction

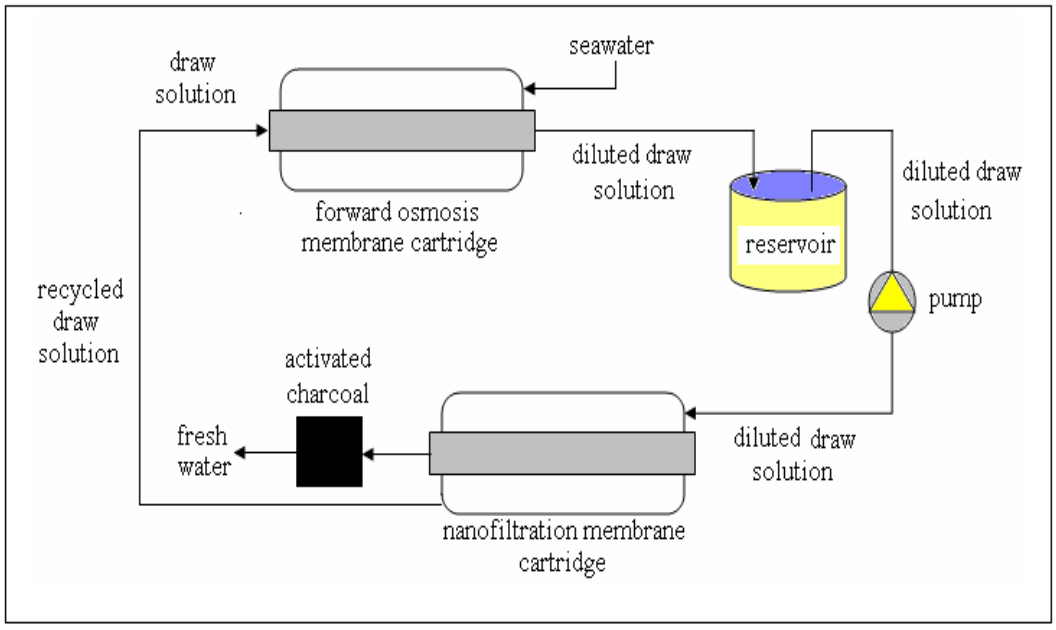
California, a region with low rainfall and high population densities and a western border on the Pacific Ocean, has the need to create new fresh water supplies from seawater using processes that are more cost effective and energy efficient. Traditional desalination methods based on evaporation and reverse osmosis require from 4000 to 15,000 kWh per acre foot of water. The

new desalination method, forward osmosis, tested in this project reduces the energy input and cost of purifying brackish water.

California ratepayers would benefit from less expensive supplies of fresh water derived from seawater using the new desalination process. The researchers demonstrated that seawater could be desalinated using 1500 to 3000 kWh per acre foot of water, a savings of up to 80% of the energy compared with traditional methods.

The new technology is forward osmosis, which consists of three main technology pathways: development of novel organic and inorganic solutes and solvents with comparable osmotic pressures to salts in seawater, utilization of forward osmosis techniques to optimize fresh water partitioning between seawater and the draw solutions, and the utilization of nano-filtration techniques to recycle the draw solutions and recover pure water. The researchers built a laboratory scale model that performed in the same manner as the conceptualized system shown in Figure 9.

Figure 9: Conceptualized Desalination System



2.9.3 Objectives

The goal of this project was to determine the feasibility of a lower cost, lower energy method of desalinating seawater: a forward osmosis process that used novel organic and inorganic solutes/solvents to create osmotic pressures across a semi-permeable membrane. The researchers established the following project objectives:

1. Demonstrate solute/solvent stability over a temperature range of 5-75°C.

2. Demonstrate the solubility in excess of 10 percent by weight in organic and inorganic solutes/solvents.

3. Demonstrate that fresh water can be separated from seawater with TDS (total dissolved solids) in the range of 5 to 50 parts per million (ppm).

4. Perform a cost analysis that shows the new desalination process would have costs no higher than $300 per acre foot of water treated.

5. Demonstrate that the forward osmosis efficiency should be able to lead to a seawater to fresh water conversion rate greater than 80%.

6. Confirm that a fresh water output of five gallons per day can be treated using the forward osmosis process.

2.9.4 Outcomes

1. After rejecting a number of inorganic solvents, the researchers studied new organic solutes in water. These had a molecular weight of approximately 350 amu, a large molecular structure which met nano-filtration membrane criteria and were compatible with the forward osmosis system. Testing with these solutes over a temperature range of 5-75°C yielded favorable forward osmosis results, as well as efficient separation of water and recycling of these draw solutions by nano-filtration.

2. The researchers determined the new organic solutes had a high solubility of ≈ 200 g/100 mL which appeared to be much higher than the goal of 10 percent by weight in water.

3. The researchers investigated several nano-filtration membranes and tested them for efficiency in separating fresh water, with a TDS of 5 to 50 ppm, from the draw solution. They tested the new organic solute identified in both forward osmosis and nano-filtration. The test results showed permeate from the nano-filtration unit process was free from the organic solute in concentrations up to 45 percent diluted draw solution. The recycled draw solution was sufficiently concentrated to be recycled back to the forward osmosis process. The researchers conducted the nano-filtration process at 200 psi, which is much lower than the operating pressures in a traditional reverse osmosis system.

4. The researchers determined that the power costs of the proposed process were $276 per acre foot (at 3,000 kWh per acre foot and $0.092/kWh).

5. Testing during the course of the project routinely removed nearly all the water from the synthetic seawater while leaving all the sodium chloride behind in the seawater compartment, with only a small layer of water. The researchers observed conversion rates of greater then 80 percent in forward osmosis with no expenditure of energy (pumping or pressurization).

6. The researchers' testing showed much higher fresh water flux than the goal of five gallons per day of fresh water.

2.9.5 Conclusions

1. While the researchers found water immiscible solvents were ineffective in forward osmosis due to their hydrophilic nature, they identified several novel organic solutes that were stable over a temperature range of 5-75°C.
2. These organic solutes were capable of high solubility much in excess of 10 percent accompanied by high osmotic pressures in water.
3. The researchers used these solutions in proving the proposed forward osmosis concept. When combined with an inexpensive nano-filtration system for draw solution recycling, they demonstrated that fresh water can be separated from seawater with a TDS (total dissolved solids) in the range of 5 to 50 parts per million (ppm). The nano-filtration membranes did require a higher pressure, 200 psi, than is optimal.
4. The cost analysis performed by the researchers included only the electricity cost. This was less than $300 per acre foot of fresh water based on relatively low electricity costs. The researchers did not consider additional operating, maintenance, and capital costs which would make the overall cost of produced water higher.
5. The laboratory work performed proved that seawater could be treated so that 80 percent of the input was recovered as fresh water.
6. The researchers assembled a complete laboratory apparatus that produced 5 gallons per day of fresh water using the forward osmosis concept.

2.9.6 Recommendations

The primary aspect of this project that needs to be optimized is the identification of new nano-filtration membranes which can function at lower pressures and have a more clearly defined molecular weight cut off point (MWCO). While commercial nano-filtration membranes obtained for testing in this project specified 200 Daltons (unified atomic mass unit) as the MWCO, the actual range varied between 200 and 500 Daltons. The Program Administrator recommends investigation of additional nano-filtration membranes with more well defined MWCO ranges and less variance. The overall cost of the forward osmosis process also needs to be better defined, including other operating and capital costs as well as energy cost.

2.9.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research would be increased affordability of electricity in California. This project demonstrated desalination of water could be accomplished with energy consumption between 1,500 and 3,000 kWh per acre foot. Reverse osmosis requires more than 3000kWh per acre foot. The researchers estimated the cost of the desalinated water between $400 and $500 per acre foot, comparable to the costs of imported water supplied in 2005 in Southern California. This compared favorably to the cost of water by reverse osmosis which was more than $600 per acre foot.

2.9.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.9.8.1 Marketing/Connection to the Market

The researches proposed, after successful development of the forward osmosis process technology, to transfer the technology free of cost to interested coastal cities and counties in Southern California. The model for technology transfer will be the open source model used for the Linux software, with any further technology development by users available to the desalination community as a whole.

2.9.8.2 Engineering/Technical

The researchers provided no details indicating further work.

2.9.8.3 Legal/Contractual

The researchers provided no evidence of patent protection.

2.9.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

There is no evidence that the researchers have done or will do work in this area.

2.9.8.5 Production Readiness/Commercialization

The researchers do not plan to commercialize this technology.

2.10 Small Wind Turbine Generator for Low Wind Speed / Low Noise Turbines

Awardee: Sonsight Inc.

Principal Investigator: Devon R. McIntosh

2.10.1 Abstract

Most people live in low wind speed areas (i.e., Class 1 or Class 2 wind sites) where wind speed is 12 to 15 miles per hour. In these areas standard wind turbines are either not effective or marginally effective. The only way to extract significantly more energy from such low wind speed sites is to increase turbine blade diameter. However, due to the limitation on blade tip

speed, blade angular velocity is inversely proportional to blade diameter. Therefore, for direct drive wind turbines, the longer blade lengths dictated by low wind speed sites require generators with significantly higher power capacities at low revolutions per minute (RPM). For current generator designs, this would require substantially more massive and costly magnetic circuit components to the point of being commercially impractical.

Another wind turbine problem area is noise. Substantially decreasing the blade tip speed would significantly reduce noise levels, but would also require significantly higher power capacities at low RPM. The central goal of this research project was to develop a half-scale prototype for a 10 kW low RPM wind turbine generator that provided the same power as standard 10 kW generators at half the rotational speed with no increase in electric or magnetic loading or total costs. If successfully developed and deployed, California based low wind speed generators could generate up to 3 percent of the electricity for the state. California produced 295,268 gigawatt hours* of electricity in 2006 from all sources. Carbon based fuels accounted for less than half of the total generation with natural gas providing about 37 percent of the total.

The researchers built a prototype generator that employed a novel axial flux stator core design. Subsequent tests combined with numerical calculations showed the generator capable of producing over 10 kW at 150 RPM. Moreover this was accomplished with significantly less mass and cost than commercially available 10 kW wind turbine generators. Cogging torque was also significantly decreased.

Keywords: Wind energy, wind turbines, turbine blade diameter, low wind speeds

2.10.2 Introduction

In California there are significant geographic areas in which wind velocity is described as "low speed."[15,16] Low speed winds are 10 to 12 miles per hour (mph) at a 30 meter height. These winds are categorized as Class I and Class 2. Current technology small wind turbines (50 KW or less) cannot effectively utilize this low speed wind. Thus significant areas and populations are not able to have wind energy as a local option to generate their electricity.

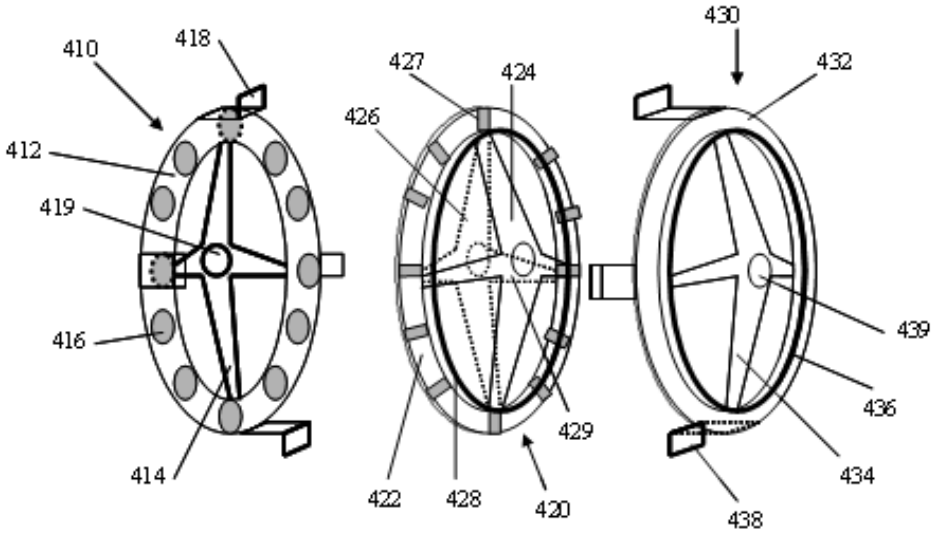
The American Wind Energy Association estimated that small wind turbines could provide up to three percent of the United States electrical demand by 2020. In areas of California where the lower wind speeds predominate this could amount to a total potential of nine gigawatt hours of energy.

If small wind turbine energy potential is achieved, wind energy could displace present carbon based fuel electrical generation in California. In 2006 California generated 37 percent of its electricity using natural gas. Displacing natural gas fuel would reduce CO_2 and NO_x emissions in the state.

The innovation proposed in this project was to generate electricity from wind in small turbines at half the usual revolutions per minute (RPM). This would greatly enhance low wind speed performance or greatly reduce noise levels, or some combination of both. The project goal was to develop a half-scale prototype for a 10 kW low RPM wind turbine generator, thereby making small wind turbines much more acceptable to the target market. The generator developed in this project was an inner rotor permanent magnet axial flux design. Figure 10 is a schematic showing the relationship of the two stator assemblies (410 and 430) to the rotor (420). Driven by

the drive shaft (not shown), the rotor rotates the permanent magnets (427) past the stator coils (416) which are assembled in close proximity to the magnets, thereby generating electrical power. To facilitate electrical power generation, magnetic flux must be established in the axial direction so as to perpendicularly penetrate the plane of the coils. This requires a magnetic circuit design in which the coil centers are linked by laminated iron that efficiently conducts the magnetic field.

Figure 10: Schematic of Permanent Magnet Axial Flux Ring Configuration



2.10.3 Objectives

The goal of this project was to prove, via a half-scale prototype, the feasibility of a 10 kW direct drive permanent magnet wind turbine generator that generates the same power as standard 10 kW generators at half the rotational speed with no increase in electric or magnetic loading or total costs. The researchers established the following project objectives:

1. Demonstrate that the prototype will generate five kilowatts of power at 150 RPM.
2. Demonstrate that the test stand is capable of measuring power and efficiency with an error of less than 3 percent.
3. Demonstrate generator efficiencies of greater than 85 percent.
4. Verify that the cogging torque is three orders of magnitude less than total generator torque.
5. Verify that operating temperatures are significantly less than the permanent magnet Curie temperature.
6. Confirm from the project findings that the projected manufacturing cost of the full scale 10 kW generator is less than $7,500.

2.10.4 Outcomes

1. The prototype that was built was not complete. The researchers assembled the prototype to check cogging torque. Only two test stator coils out of the total of 56 coils were installed. Therefore total generator power was projected based on measurements from a prototype with only two coils. Each of these two coils consists of 145 loops of AWG (American Wire Gauge) 21wire, and occupied about 20 percent of the available coil space. The power generated at 150 RPM was measured at 367 watts. The calculated power if the full-sized prototype had been built was estimated at 8.7 kW. When AWG 15 wire was used, the actual power output increased to over 500 watts in the prototype. The researchers estimated full-size power at 12 kW. Thus the goal of at least 10 kW at 150 RPM appeared to be reachable.
2. The researchers calculated the total measurement error by error propagation of individual tolerance specifications. The power output error based on the instrumental tolerances was 3 percent, and the power input error was 0.2 percent. The combination of these errors for the overall generator efficiency error was 3.3 percent, close to the stated goal of 3 percent.
3. The researchers were not able to measure efficiency at very low input powers and to project this value to higher powers. As a result, the researchers did not indirectly measure total generator efficiency.
4. The researchers measured the cogging torque at 1.5 Newton-metre (N-m) compared with the full power torque of 706 N-m. The cogging torque was only 1/500th of the full torque.
5. The inner rotor design produced significantly better heat dissipation because the major heat generating elements (i.e., the stator coils) were separated into two sets, thereby improving cooling. Therefore the researchers did not analyze operating temperatures within this development phase
6. The researchers assumed the projected manufacturing cost for the generator to be the same as the cost of materials used to build the prototype. The total material, labor, and overhead costs for the 10 kW generators were $7,045, less than the $7,500 projected cost.
7. This outcome was added to the original list. For the 10 kWgenerator, the projected mass of the inner rotor permanent magnet axial flux design was approximately 327 pounds, which was less than half that of a conventional 10 kW wind turbine generator (often over 1000 pounds).

2.10.5 Conclusions

1. Although the full-sized prototype of 10 kW was not actually built and tested, a partial-size prototype produced 500 watts. Based on scaling factors, the full-sized unit would produce over 10 kW. The researchers based this calculation on an assumed 85 percent efficiency, which they did not measure during the tests.
2. The testing equipment had an acceptably low error of 3 percent in measuring power.

3. The researchers did not measure efficiency.
4. Generator cogging torque was similar to that of machines of much lower power.
5. Heat dissipation may be an issue when all 56 coils are installed. This must be investigated in future studies.
6. This generator design should allow shorter turbine payback periods for small wind turbines. The low generator mass should allow decreased installation costs, and with an overall lower cost of the turbine, there should be shorter payback periods.
7. The low RPM generator should provide for significantly quieter turbines. The testing of the partial-sized prototype did indicate the prototype's power to weight ratio significantly exceeded that of other generators.

The researchers partially proved feasibility of this concept of a lower cost wind turbine for low wind speed. The generator was constructed, but only 2 coils of 56 were actually installed and tested. Many of the conclusions were based on calculated power outputs from the incomplete prototype.

2.10.6 Recommendations

1. The possibility of generating several times more power from essentially the same generator package is intriguing. Finite element thermal modeling and electrical configurations for minimizing output impedance should be investigated to determine power generation limits. This should also be accompanied by high power temperature measurements of a complete prototype.
2. The stator and rotor reinforcements were done somewhat ad hoc. These should be designed to be more efficient and effective.
3. The entire design should be optimized for manufacturing.
4. The magnet to coil ratio could be optimized to reduce cogging torque further and improve power generation.
5. A full set of coils should be installed and options investigated for combining the various AC phases into a DC output. This includes development of the rectifier and analysis of the power factor.
6. Efficiency as a function of RPM and temperature should be determined.
7. Research should be undertaken to incorporate the generator within a low wind speed turbine suitable for DOE Class 1 and Class 2 wind sites.
8. The researchers should conduct a market assessment to determine more accurately the market size for low wind speed turbines.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.10.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is the reduced environmental impacts of the California electricity supply, transmission, and distribution system. Using advanced low speed wind generators, nine billion kWh of energy could be generated annually within California from the state's low wind speed sites with 100 percent market penetration. Assuming natural gas power plants emit one pound of carbon dioxide per kWh, California could eliminate nine billion pounds of carbon dioxide per year if the small wind turbine energy potential is achieved and it replaces present natural gas fueled electrical generation. Low wind speed turbines could help the investor owned utilities meet the state mandate for renewable energy generation.

2.10.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.10.8.1 Marketing/Connection to the Market

The investigators identified the potential market as residential, commercial, industrial, and government clients, but did not have a specific plan for bringing the technology to the market.

2.10.8.2 Engineering/Technical

The investigators indicated these technical challenges remained:

1. Develop better stator reinforcement.
2. Develop the rectifier and analysis of the power factor.
3. Incorporate the generator within a wind turbine.

2.10.8.3 Legal/Contractual

None known

2.10.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

None of these plans had been completed at the end of this project.

2.10.8.5 Production Readiness/Commercialization

The recommended follow-on research must be completed before commercialization of this generator. The principal investigator planned to utilize grants to incorporate the generator in a low wind speed turbine. He also planned to use grants and investors to fund manufacturing and marketing studies.

2.11 A Three Phase Grid Tied Inverter That Suppresses Harmonics and Reactives

Awardee: One-Cycle Control, Inc

Principal Investigator: Gregory T. Smedley

2.11.1 Abstract

Distributed Generation (DG) can reduce local energy costs by providing peak shaving and cogeneration of heat and power. It can also reduce delivery requirements of the supply side generation and transmission and distribution systems. Many applications that may benefit from DG have very high power quality requirements or impose power quality concerns for the grid. Meeting these requirements may be expensive using the common grid for small systems.

This project demonstrated a one cycle control (OCC), five kilowatt, three phase power converter that functioned both as a grid tied inverter (GTI) and as a power quality filter (PQF) to suppress harmonics and improve power factor. The prototype delivered up to 5 kilowatts of grid tied power, suppressed harmonics to 5 percent from 27 percent, and improved power factor to 1.0 from 0.7. The developed device performed two functions and therefore delivered a potential cost saving in the balance of plant for many DG applications. The combined GTI/PQF may lead to decreased capital, installation, maintenance, and electricity costs compared to individual GTI and PQF.

Keywords: One cycle control, distributed generation, power quality, power factor, harmonics, grid tied inverter, power quality filter

2.11.2 Introduction

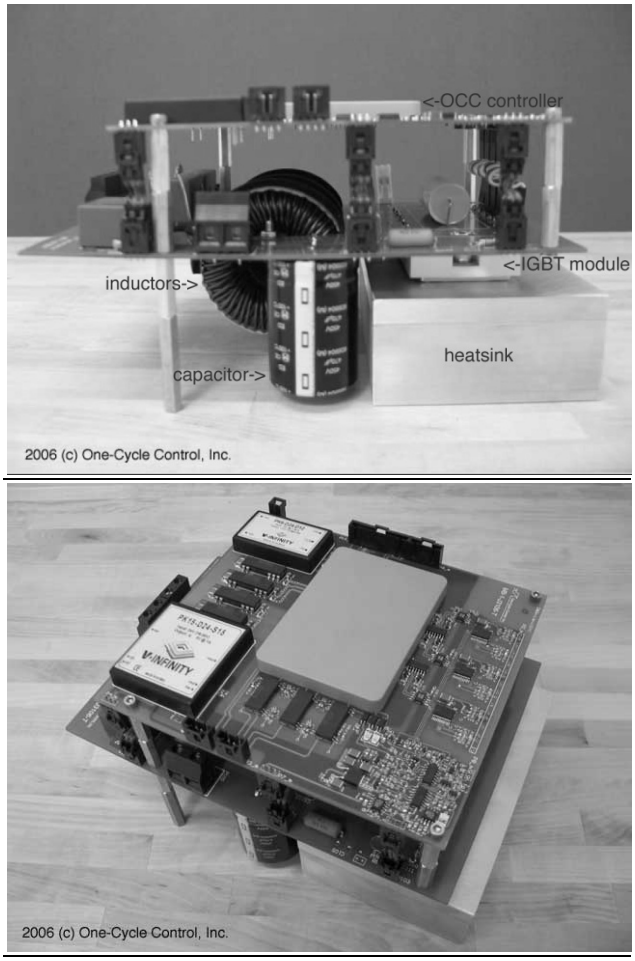
Distributed Generation (DG) can reduce local facility electricity costs by providing peak shaving and cogeneration of heat and power. It can also reduce delivery requirements of the supply side generation and transmission and distribution system, while improving certain power quality factors. Many applications that may benefit from DG have very high power quality requirements (e.g., harmonics and frequency control) or impose power quality concerns for the grid. Many renewable energy generation technologies require an inverter to connect to the grid.

Inverter cost can be a significant percentage of the installed costs. Often when installing distributed generation, especially photovoltaic systems or fuel cells, one must purchase both an inverter and power quality filter. At the time this project was started no product was offered commercially that performed both functions. A single device performing both functions could lower the overall cost of installing distributed generation.

Reducing the costs and improving the ease of installation for distributed generation should accelerate the adoption of small photovoltaic and fuel cell systems by residential, commercial, and industrial users.

This project demonstrated a one cycle control (OCC), 5 kilowatt three phase power converter that functioned both as a grid tied inverter (GTI) and as a power quality filter (PQF) to suppress harmonics and improve power factor. If production costs prove to be favorable, this device should accelerate the use of distributed generation. Local distributed generation could reduce power line losses and improve energy efficiency through the use of cogeneration. Figure 11 illustrates the device.

Figure 11: Assembled 5 Kilowatt 3 Phase GTI/PQF without Enclosure



2.11.3 Objectives

The goal of this project was to prove the feasibility of using a single device to provide both inverter and power quality filtering functionality for distributed generation applications. The researchers established the following project objectives:

1. Conduct system analysis to demonstrate grid tied inverter (GTI)/power quality filter (PQF) operation under steady state and dynamic conditions.
2. Verify prototype functionality with basic enclosure design.
3. Demonstrate 5 kilowatt GTI operation.
4. Demonstrate 30 percent reactive power compensation.
5. Demonstrate 30 percent harmonic compensation.
6. Demonstrate 30 percent combined reactive and harmonic compensation.
7. Demonstrate corrected power factor greater than 0.99.
8. Demonstrate corrected total harmonic distortion (THD) less than 5 percent.
9. Confirm targeted manufacturing cost below $300 per kilowatt.

2.11.4 Outcomes

a. The researchers conducted comprehensive system analysis of the device under steady state and dynamic (e.g., varying load) conditions.

b. The researchers tested the prototype for both GTI and PQF functions with a basic enclosure.

c. The inverter functionality delivered 5.1 kW of electrical power to the simulated grid.

d. The researchers demonstrated a reactive power compensation of 30 percent.

e. The researchers achieved harmonic compensation of load with 26.9 percent THD.

f. The researchers demonstrated a combined reactive compensation of 8 percent and harmonic compensation of 16.8 percent under combined load.

g. The researchers achieved a corrected power factor of 1.00 under a variety of simulated operating conditions, including switching loads.

h. Corrected total harmonic distortion (THD) of 3.8 percent was achieved in combined GTI/PQF mode and THD of 2.0 percent in GTI mode, under a variety of simulated operating conditions.

i. Based on the printed circuit boards, hardware, and components used to construct the prototype, the researchers estimated manufacturing cost for a 5 kilowatt OCC enabled GTI/PQF to be approximately $1400 per unit ($280/kW) in quantity of 10 units. This estimated cost included: complete converter with circuit breaker, thermal management system, NEMA 1 type enclosure, in rush current limiting, full protection (surge, over

voltage, under voltage, over current, over temperature), and complete motherboard with OCC controller. Conformal coating (if required) and IEEE1547 shut down requirements for frequency/voltage conditions were not included. These must be designed into a commercial version of the prototype.

2.11.5 Conclusions

The researchers successfully demonstrated that multifunctional inverter and power quality filtering can be physically achieved. The primary conclusions of this project were:

- Combined functionality of inverter and power quality filtering is achievable in single devices.
- Improved cost and performance may be achieved compared to multiple component uses.
- Not all distributed generators require the GTI functionality (e.g., micro-turbines) as some produce alternating current power directly. This may limit market potential. Not all DG applications (e.g., PV) that require inverter capability also require power quality filtering, as most modern inverters provide high power quality. The power quality capability would provide for filtering of grid sourced power quality issues.
- The cost analysis presented in the final report gave an indication of manufacturing cost but was not sufficient for market assessment purposes.

2.11.6 Recommendations

The researchers should complete a comprehensive cost analysis that includes all components necessary to meet utility rules for interconnection. The cost analysis must be extended into a user price for the completed device. At that point the researchers should undertake a side by side cost comparison of the one cycle controller with separate GTI and PQF components. The researchers should consider initial cost, parasitic loads, durability, and reliability. The analysis should be clearly documented and state all assumptions.

The researchers should also undertake a comprehensive market assessment to determine the portion of the DG market that requires both inverter and power quality filter functionality. The study should include the needs of California electric utilities. Finally, the researchers should work directly with manufacturers and packagers of DG prime movers to incorporate the devices' inclusion in package units to facilitate market acceptance and adoption.

Finally, the researchers should work directly with at least one electric utility to ensure that the device will be approved by utilities for grid interconnection. Utilities have strict safely and anti-islanding rules to ensure the well-being of their employees and customers.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.11.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. Reduced environmental impacts of the California electricity supply system are a secondary benefit.

Distributed generation applications can provide cost savings to users. To the extent that this multi-function device lowers the cost even further compared to multiple component usage, expanded or more rapid deployment of DG may occur.

A 1 percent decrease in annual state-wide supply side grid generation (i.e., a reduction of 2.38 billion kWh) could be achieved if 12 percent of industry customers installed 100 kW of on site generation or 5 percent of commercial customers installed 10 kW of on site generation (if both, then a 2 percent reduction might be achieved.) The market penetration levels of distributed generation could be increased if the costs of control and interconnect electronics were significantly reduced. The work in this project was aimed at reducing the cost of the inverter circuit and the power quality circuit. Given the economy of scale for the cost of the combined electronics, market penetration would be higher in larger industrial applications.

The PQF functionality reduces the harmonics in the transformers of these facilities providing an approximately 2 percent improvement in transformer efficiency. Improved power quality resulting from the PQF also provides savings to California industry and commercial sectors that are difficult to estimate. However, estimates of losses due to poor power quality are usually measured in billions of dollars, especially as the California economy continues a structural shift to higher technology manufacturing and services.

2.11.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.11.8.1 Marketing/Connection to the Market

The researchers have not undertaken market research nor surveyed potential vendors or customers of the concept controller. There has been no expressed interest by industrial or commercial companies in commercializing the technology. The researchers believe they can commercialize the technology without partnering with other companies, but do plan to find a commercialization partner. Improving market connection would be facilitated by the researchers working directly with prime mover manufacturers and packagers.

2.11.8.2 Engineering/Technical

The major technical issue that the researchers need to address is standards compliance and listing. Compliance and listing cannot be completed until product sizing (how many kW) and enclosure issues are dealt with, along with safety issues as noted below.

2.11.8.3 Legal/Contractual

The researchers had not completed a patent search, but patents have been issued for power converter components.

2.11.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

The researchers should test to failure the product in various sizes to facilitate UL listing. Further, product quality manufacturing plans should be developed.

2.11.8.5 Production Readiness/Commercialization

It appears that emphasis has been entirely on the technical demonstration of certain performance objectives. This is consistent with the statement of work, but leaves the commercialization of the technology in jeopardy. The technology is not yet ready for production or commercialization. In addition to the technical issues noted above, product packaging and test to failure and safety certification are required.

2.12 Computer Controlled LED Traffic Light Power Supply Controller Time Diagnostic of Transformer Oil

Awardee: California State Polytechnic University Pomona

Principal Investigator: R. Frank Smith

2.12.1 Abstract

Traditionally, large light emitting diode (LED) arrays used in traffic lamps and commercial signage applications were constructed of multiple LEDs connected in series to a power source. This configuration has several significant drawbacks including: failure of an entire string of LEDs connected in series with a defective LED, and large drive voltage requirement that may pose a safety hazard. The researchers proposed an alternate parallel circuit configuration that

would mitigate these issues and also improve the efficiency of the LED array. The researchers capitalized on recent advances in power supply components, as well as improvements in LED uniformity through a manufacturer process called binning. That process reduces the standard deviation with a lot of LEDs. The research team built and tested five LED arrays and measured a 62 percent power consumption savings over traditional LED arrays.

The research team investigated alternative drive circuit topologies that powered the LEDs in a parallel arrangement, rather than the commonly occurring series arrangement. The alteration in the circuitry allowed for an 89 percent improvement in circuit efficiency and a 62 percent reduction in power consumption.

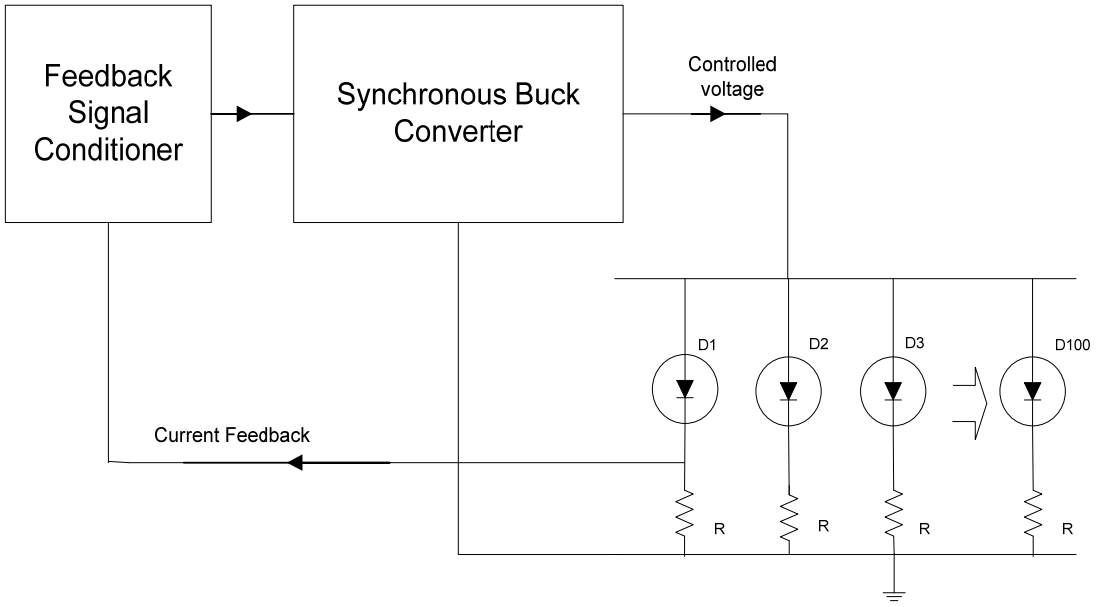
Keywords: Light emitting diodes, LEDs, LED arrays, traffic lights, power supplies, synchronous buck converters, FPGA, current feedback, commercial signage, pulse width modulation

2.12.2 Introduction

The US Department of Energy State Energy Program estimates that there are 40,000 intersections with 1.8 million traffic lamps in California. By 2004 approximately half of those had been replaced with LED lamps, saving approximately 60 MW in power over incandescent lighting, which consume 90 percent more power than LEDs. LEDs are not only energy efficient, but also offer a tremendous replacement and maintenance savings due to their typical 10,000 hour lifespan. The trend toward adoption of LED technology is quickly accelerating to reap these benefits in traffic control lighting, as well as signage, cell phones, reading lamps, and many other applications.

Traditionally, large LED arrays used in traffic lamps and commercial signage applications were constructed of multiple LEDs connected in series to a power source. This configuration has several significant drawbacks including: failure of an entire string of LEDs in the event of the failure of one LED, and large drive voltage requirement that may pose a safety hazard. The researchers proposed an alternate parallel circuit configuration that would mitigate these issues and also improve the efficiency of the LED array (Figure 13). The researchers capitalized on the recent advances in power supply components, as well as improvements in LED uniformity through manufacturer binning to construct the LED arrays, while reducing energy consumption of the drive circuit. The research team built and tested five LED arrays and measured a 62 percent power consumption savings over traditional LED arrays. The most successful topology is shown in Figure 12.

Figure 12: Block Diagram of Analog Circuit with Current Feedback



The researchers estimated that incorporation of this alternate LED array configuration into traffic lamps could save $1.3M annually for every 100,000 signal heads. Extending the savings to the approximate lamp quantity determined in the 2004 US Department of Energy State Energy Program study, this could lead to a savings of $23.4M. This savings is the incremental benefit by using the proposed circuit topology rather than the traditional LED driver circuitry, assuming all incandescent traffic lamps in the state ultimately converted to LEDs.

2.12.3 Objectives

The goal of this project was to improve the energy efficiency of large LED arrays such as advertising displays and traffic control devices by establishing and demonstrating the feasibility of innovative low cost driver circuits. The researchers established the following project tasks and objectives:

1. Develop and simulate by computer different circuit topologies.
2. Optimize a candidate circuit topology and then re-simulate it to verify operation. Demonstrate that the chosen circuit topology theoretically meets the design criteria.
3. Design and fabricate circuit boards.
4. Test a prototype LED array the same size as commercial traffic signals (approximately 200 LED array) using the candidate circuit topology.
    a. Measure the power conversion efficiency (η), power factor (pf), temperature degradation (lumens per degree centigrade), spectral illumination (lumens), and luminous efficacy (L/W). Compare measurement results between test circuit and commercial traffic signals.

b. Demonstrate that the circuit topology is capable of reducing power consumption by 20 percent.

c. Demonstrate that the circuit topologies reduce the 24 hour root mean square (rms) junction temperature by 20 percent.

d. Demonstrate that the circuit can operate at both minimum and maximum voltages established by local utilities.

e. Demonstrate that the different circuit meets the requirements of existing standards such as the Federal MUTCD 2003 (Manual on Uniform Traffic Control Devices) and the MUTCD 2003 California Supplement, Sections 9-00 through 9-05.

5. Develop test protocol. Demonstrate that the test protocol detects defective out of compliance circuit boards.

2.12.4 Outcomes

1. The researchers designed and simulated two analog and one digital circuit topologies.
2. The project team used computer simulation to reach a final design topology for both the analog and digital topologies, iterating until the circuits met performance specifications. The researchers did not state the target specifications or the results of the computer simulations.
3. Of the three circuit topologies simulated, one analog and one digital circuit was constructed and tested.
4. The prototype LED array consisted of an analog synchronous buck converter driving an array of 100 red LEDs at a constant current.

    a. None of the proposed LED output measurements were reported. Rather, the LED array was analyzed for candelas. The researchers determined that the prototype light output of the LED array was 366 candelas. Results were not compared to those obtained from commercial traffic signals. The light output was twice the minimum output of 162 candelas recommended by the Institute of Traffic Engineers (ITE) for a 200 mm red LED lamp.

    b. The prototype had a power rating of 4.2W. This is approximately 62 percent less than the 11.3W power rating of the commercial red LED traffic signal lamps that were tested.

    c. The researchers stated that the circuit topologies reduced the 24 hour root mean square (rms) junction temperature by more than 20 percent. The actual amount of reduction and supporting data were not presented.

    d. The luminescence of the analog circuit remained constant when operating from the minimum to maximum voltages of 114 V and 126 V supplied by Southern California Edison.

e. The researchers did not compare the prototype circuit to any design standards.

5. The researchers developed two tests to identify defective LED circuit boards. The researchers stated that the tests could identify defective circuit boards but were unable to isolate problems to a component level.

2.12.5 Conclusions

1. The researchers met the objective to develop and simulate different circuit topologies. Although the researchers' proposed scope of work included a large number of tests to be performed on the circuits, none of the results were presented. Proposed testing in the grant application was shown as follows:

    a. Power consumption (watts)

    b. Operating voltage (volts)

    c. LED characteristic curves using high speed data acquisition equipment (light-current-voltage LIV characteristics)

    d. Total harmonics generated by the circuit, both voltage and current. These will be measured using a power harmonic analyzer.

    e. Inrush current (amperes). These will be measured using a high speed digital oscilloscope.

    f. Spectral illumination including chromaticity using an integrating sphere and associated spectrophotometer.

    g. Relative temperature degradation using a temperature controlled oven and photo sensor and data acquisition equipment.

2. The Program Administrator could not adequately evaluate if this objective was met. Performance specifications were not included in the report. The researchers described a process by which the team analyzed 15 commercial traffic control signal heads to evaluate operating characteristics. The results of the analysis and any derived operating characteristics were not included in the final report. Further, the report did not contain any information regarding sensitivity analysis using Monte Carlo simulation, as described in the researchers' grant application project tasks. Ultimately, the researchers selected to proceed with the analog circuit topology, stating that it resulted "in a more viable commercial circuit than incorporating a temperature feedback signal to control the operating point." There is no explanation regarding the definition of "viable" in this case nor are any technical data presented to support the claim.

3. The researchers met the objective to design and fabricate circuit boards.

4. The researchers failed to construct a prototype LED array the same size as commercial traffic signals (approximately 200 LED array), but rather constructed one half of the target size.

a. The researchers failed to measure any of the proposed output characteristics of the prototype. The proposed measurements, given in lumens or related, are indicators of light output at the source, whereas the reported measurements, given in candelas or related, are indicators of light that falls on a surface. The researchers failed to compare prototype results to commercial traffic signals. Instead comparisons were made to the 1998 traffic light recommendations for a 200 mm traffic light, as presented by ITE. The ITE specification used for comparison is not an actual test result, but rather a minimum acceptable recommendation. The logic for using this standard is not clear, as the degree to which existing commercial technology exceed the standard was not established in the report.

b. It is not possible to verify if the circuit topology is capable of reducing power consumption by 20 percent. The 11.3 W average power rating stated for the commercial red LED traffic lamps tested was higher than either of the two tabulated values presented in Table 1 of the final report.

c. No experimental procedures or results were presented to verify successful goal achievement.

d. No supporting data were presented in the final report to demonstrate that the circuit could operate at both minimum and maximum voltages established by local utilities.

e. The researchers failed to meet the objective to demonstrate that the different circuit meets the requirements of existing standards such as the Federal MUTCD 2003 (Manual on Uniform Traffic Control Devices) and the MUTCD 2003 California Supplement, Sections 9-00 through 9-05.

5. The researchers met the objective to develop test protocol. The researchers presented no experimental data to support the claim that the test protocols were effective in identifying defective circuit boards.

Many tests which may have been done were not described at all. Because almost no results were presented, arguments that objectives were reached are unsubstantiated.

2.12.6 Recommendations

The Program Administrator recommends that the researchers issue a more complete report including test methods, data, and analysis. While it appears that feasibility was proven in the project, the researchers must establish greater confidence in their findings by more complete disclosure of results. The researchers may be withholding complete test information pending successful patent actions. The researchers implied a strong research link with Texas Instruments. That link should be more fully disclosed. A commercial link of this type could be beneficial to rapid commercialization of the project results.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the

Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.12.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. The researchers estimated that a savings of $1.3M annually for every 100,000 signal heads could be realized through the use of the proposed technology. Extending the savings to the approximate lamp quantity determined in the 2004 US Department of Energy State Energy Program study, this could lead to a savings of $23.4M in California. This savings is the incremental benefit by using the proposed LED circuit topology rather than the traditional parallel style LED lamps, assuming all incandescent traffic lamps in the state ultimately converted to LEDs.

2.12.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.12.8.1 Marketing/Connection to the Market

The researchers have strong links with Texas Instruments, a manufacturer of LEDs. Texas Instruments could be an excellent partner to take the circuit topology developed in this project to market.

2.12.8.2 Engineering/Technical

The researchers planned to continue the project work. Specifically they planned to build and test the second analog circuit that passed the computer simulation tests.

2.12.8.3 Legal/Contractual

The researchers have performed a rudimentary patent search and have not identified any potential infringements.

2.12.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

Because of technology immaturity, these plans have not been developed.

2.12.8.5 Production Readiness/Commercialization

Texas Instruments is capable of assisting the researchers in preparing the technology developed in this project for commercialization.

2.13 Nanocable Structures for Solar Cell Application

Awardee: Q1 NanoSystems Corporation

Principal Investigator: Ruxandra Vidu,

2.13.1 Abstract

The object of this project was to develop a new photovoltaic (PV) technology based on recently discovered nano-cables, multi-layered nano-wires. Nano-cables are bristles in a solar brush to be used in a PV cell structure. This technology has the promise of producing solar cells at lower cost than conventional bulk crystalline silicon cells. The solar brush architecture is of interest because it could increase the optical path through the PV material while reducing the amount of material used by up to 90 percent. In addition, this architecture would increase light trapping in the cell by providing a broader range of solar acceptance angles. The approach uses electrochemical processes to create nano-porous membranes as templates in cell growth. This research was successful in demonstrating that the bristle structure using conventional materials and processes can be economically incorporated into thin films manufacturing. The project also demonstrated robust bristle structures at significantly greater aspect ratios than those proposed. The major goal was to integrate metal/semiconductor junctions into the nano-structured bristles and to incorporate them into individual working solar cells. However this project did not achieve working junctions in bristles and working solar cells. Therefore it did not establish feasibility of this approach.

Keywords: Integrated nanostructures, array, nano-cables, nano-wires, photovoltaic, CdTe, CdS, thin film

2.13.2 Introduction

California ratepayers would realize significant benefits if the state's electricity generation could be shifted from carbon based fuel energy sources to lower cost non-carbon renewable sources. The air quality would improve and the future cost of electricity would be less dependent on the rising cost of carbon based fuels. At the present time, renewables (biomass, geothermal, hydroelectric, solar, wind) comprise only 11 percent of California's electricity production, while

carbon based fuel sources account for 57 percent.[13] The solar component of the renewable mix is especially attractive because it is well matched to California's abundant year round sunshine and to its electrical demand which peaks in the afternoon on hot summer days. Solar photovoltaic (PV) systems are attractive because they provide direct conversion of solar energy to electricity with few moving parts, and the technology is scalable from small scale distributed generation to large scale central power plants. The chief barrier to wider use of PV generation of electricity has been the high initial cost and limited production capacity of the market dominant bulk crystalline silicon cells. Thin film based solar cells use much less material and, if they can be manufactured from low cost materials using high volume manufacturing techniques, they could greatly improve the economics of PV systems.

The two limitations of high cost and limited production capacity have held back greater penetration of photovoltaics into the electrical generation marketplace. Solar module cost today accounts for 50-60 percent of the total installed cost of a solar energy system.[14] Therefore solar module price is the key element in the total price of an installed solar system. Crystalline silicon modules dominate, comprising 93 percent of the PV market.[15] More manufacturing capacity would help drive down prices, but what is needed is a new wide scale different technology from crystalline silicon. The payback time of PV systems also depends critically on the cost of carbon based fuel generated electricity.[16] There is evidence that the polychrystalline silicon market is the most capacity constrained part of the PV chain.[17,18] The photovoltaic industry has established a 2010 industry cost goal of $1.50/Wp for PV modules, which would make PV broadly competitive in the residential market without subsidies. However the lowest retail price today (June 2008) for the important crystalline silicon solar module market is $4.17 per watt. A lower cost cell technology with high production capacity would be a major advancement in PV technology.

To make this advancement, the researchers proposed to develop a new thin film PV technology which they called the solar brush on an inexpensive substrate. The advantages of this method would be high absorption of solar radiation in the fine bristles of the brush and efficient conversion of absorbed light to electricity in a bristle. The bristles can be thought of asIndividual solar cells which are connected in parallel on the substrate.

2.13.3 Objectives

The goal of this project was to determine the feasibility of a completely new architecture and fabrication method for very low cost, highly efficient nano-structures array for solar cells. The approach to synthesis of core/multiple shells structures with nano-scale controlled p-n junctions

13 http://www.energy.ca.gov/html/energysources.html

14 http://www.solarbuzz.com/ModulePrices.htm

15 http://www.solarbuzz.com/Technologies.htm

16 http://www.solarbuzz.com/Consumer/Payback.htm

17 http://www.solarbuzz.com./Marketbuzz2008-intro.htm

18 http://www.earth-policy.org/Indicators/Solar/2007.htm

was based on a finely tuned deposition process of ultra thin semiconductor films recently developed by Q1 NanoSystems in conjunction with University of California, Davis. The researchers established the following project objectives:

1. Determine template synthesis conditions for nano-structure preparation.
2. Produce nano-structures with an aspect ratio (height/diameter) greater than 30 and having metal/semiconductor junctions.
3. Demonstrate layer by layer deposition of CdTe and CdS thin films.
4. Demonstrate heteroepitaxy is achieved at relative low temperature, i.e., 300 K.
5. Demonstrate structures containing a core and multiple shells.
6. Demonstrate capability for interfaces in nano-scale building blocks with high surface area.
7. Demonstrate the proposed manufacturing process is capable of producing uniform structures of 100-150 nm in diameter and 3-10 microns in height in a uniform array.
8. Demonstrate more than 22 percent peak efficiency as confirmed by NREL testing.
9. Confirm the electrical advantage of a reduced transport path by conductivity measurements.
10. Demonstrate 25 percent peak performance gain over baseline (planar architecture) as confirmed by NREL testing.
11. Demonstrate 35 percent total performance gain over baseline as confirmed by NREL testing.

2.13.4 Outcomes

1. To synthesize Au nano-wire arrays, the researchers investigated two types of commercial porous templates, polycarbonate track etch membranes (PCTE) and anodized aluminum oxide (AAO) membranes and two methods of Au deposition, electroless deposition and electrochemical deposition. In addition, they investigated different chemical solutions for deposition. From scanning electron microscopy (SEM) and transmission electron microscopy (TEM) results, they eliminated electroless deposition process as a template process because the deposits lacked structural robustness for follow-on processing. They investigated two solutions for electrochemical deposition, Au(III) chloride hydrate and Au(II) cyanide electrolyte (Orotemp 24) solution. The researchers adopted the commercial Orotempt solution for later work, since it provided the most reproducible results. The researchers spent considerable effort on optimizing deposition condition. The AAO template was fragile, and it was difficult to create a reliable electrical contact for deposition. Therefore they focused on PCTE membranes. They developed a procedure for successfully dissolving the membrane after nano-rod deposition. Using this procedure, they successfully fabricated nano-rod arrays for further research. The PCTE membrane, however, did have a distribution of pore

angles with respect to the surface normal which degraded the uniformity of the resultant nano-rod arrays.

2. The researchers reported that nano-structures were produced with aspect ratios (height/diameter) of 50. However they did not report quantitative analysis such as SEM data for height and diameter. The researchers subsequently coated some metal rod arrays with CdTe, which is presumably semiconducting, but they did not present electrical data or junction measurements on the deposited CdTe.

3. The researchers subjected gold nano-arrays to electrodeposition of CdTe followed by electrodeposition of CdS. They expended considerable effort on developing chemical solutions and electrical deposition conditions. They demonstrated presence of CdTe deposits on arrays by Energy Dispersive X-ray Spectroscopy (EDS) analysis in an SEM. Proof of CdS was more difficult because of an overlap of an S x-ray line with that of Au. TEM analysis and x-ray diffraction analysis (XRD) later identified S as being present.

4. The researchers demonstrated electrodeposition of CdTe on Au nano-rods at room temperature. However they did not give XRD data to support heteroepitaxial growth relationship between either Au and CdTe or CdTe and CdS deposits.

5. Elemental analysis and XRD indirectly supported Au, CdTe, and CdS being present in the same Au nano-rod sample. However the researchers presented no direct imaging data to show a multiple core structure having concentric annuli of materials.

6. The researchers did not present data demonstrating interfaces. Therefore the presence of interfaces could only be indirectly inferred from the growth conditions.

7. Qualitative imaging data the researchers presented lent some support to rod sizes in this range, but the rods in the arrays were non-uniform, especially in angular orientation. The researchers identified the starting template as having irregularly oriented pores which caused the non-uniformity.

8. Attempts to measure a photocurrent in devices under illumination yielded no response. The researchers concluded there was a high degree of internal shorting in the devices.

9. The researchers did not perform electrical characterization measurements.

10. The researchers did not obtain these performance measurements.

11. The researchers did not obtain these performance measurements.

2.13.5 Conclusions

1. The researchers developed a successful synthesis procedure consisting of PCTE template, Orotemp 24 solution, and electrochemical deposition to synthesize Au nano-rod arrays. They identified a problem with the angular distribution of pores in the template for consideration in future work. This objective was substantially met.

2. The researchers reported nano-structures with aspect ratios (height/diameter) of 50, but they did not provide quantitative analysis for height and diameter from SEM data. They

coated metal rod arrays with CdTe, but did no electrical measurement. Therefore this objective was only partially met.

3. The researchers inferred from indirect chemical analysis evidence that this objective was met.
4. The research demonstrated electrodeposition of CdTe on Au nano-rods at room temperature, presumably below 300 K. It was not clear there was an actual heteroepitaxial growth relationship between Au and CdTe or CdTe and Au. It was not clear this objective was met.
5. Elemental analysis and XRD indirectly supported deposited Au, CdTe, and CdS were present in the same Au nano-rod sample. However the researchers presented no direct imaging data to show multiple core structure. There was only indirect evidence that this objective was met.
6. The researchers did not present data demonstrating interfaces. This objective does not appear to have been met.
7. Uniform arrays were not made, and thus the researchers did not meet this objective. However a case could be made for showing the process is capable of uniform arrays provided a PCTE template with uniform pore structure could be identified.
8. There was no response to attempts to measure a photocurrent in devices under illumination. The researchers concluded there was a high degree of shorting in the devices. Therefore they did not meet this objective.
9. The researchers did not perform electrical characterization measurements. Thus they did not meet this objective.
10. The researchers did not meet this objective due to the lack of a working device.
11. For the same reason as above, the researchers did not meet this objective.

2.13.6 Recommendations

Judging from the irregular orientation of the nano-rod arrays produced with ion track etched PCTE, a better template with a more regular pore distribution is needed. It could be useful to prepare a set of layered PV samples in conjunction with nano-rod array sample. In this way a baseline for electrical characterization and photo response of junctions could be established. In the same vein, it could be useful to pick a single nano-rod for PV testing and electrical characterization, perhaps using scanning tunneling technologies. Overall, many of the goals/objectives appear to have been too ambitious. Future work should be based on a more modest set of near term goals.

2.13.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California electricity supply, transmission, and distribution system.

Wide deployment of an efficient PV technology would bring important benefits to air quality by displacing carbon based fuel combustion in electricity generation. Today 57 percent of California's electricity is generated by carbon based fuel combustion. This 57 percent is comprised of 41.5 percent generated by natural gas and 15.7 percent by coal. On average, each kWh of coal generated electricity releases about two pounds of CO_2 and close to one pound of CO_2 by natural gas.[19] For today's mix of fuel sources in California, including non-fossil sources, each kWh of electricity that is consumed releases about 0.73 lb CO_2 into the atmosphere. California's (2005) total electricity consumption was $254x10^9$ kWh which, assuming California's in state mix of sources, contributed $93x10^6$ tons of CO_2. Such carbon based fuel produced CO_2 is now regulated as an air pollutant due to its global warming potential. In addition, other carbon based fuel emissions such as NO_x, SO_x, CO, and VOCs are also regulated.

2.13.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.13.8.1 Marketing/Connection to the Market

The researchers had been publishing in this general area for several years prior to the start of this project.

2.13.8.2 Engineering/Technical

Technical feasibility has not yet been established due to the lack of a working device.

2.13.8.3 Legal/Contractual

The researchers filed several patent applications prior to the start of this grant.

2.13.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

These plans are premature for the current state of the project. Some of the materials used, Cd and Te, have well known hazard potential, but their proper use is well established in industry.

19 http://www.seen.org/pages/db/method.shtml

2.13.8.5 Production Readiness/Commercialization

Important research questions are still unanswered, and the feasibility of the technique has not been established.

2.14 Passively Pitchable Smart Blades for Improving Efficiency of Small Wind Turbines

Awardee: Appa Renewable Energy Systems Incorporated

Principal Investigator: Kari Appa

2.14.1 Abstract

The goal of this project was to determine the feasibility of designing small wind turbines that can passively pitch their blades for maximum energy production in all wind speed conditions while being environmentally and aesthetically appealing to rural and urban community settings. Large scale wind turbines use active servo-controllers to adjust blade pitch during operation to optimize efficiency in varying wind conditions. However this technology is cost prohibitive for small wind turbine applications which typically rely on fixed blades. The researchers proposed to integrate a passive pitch control (PPC) device that would mount to the rotor, allowing the turbine blades to rotate to achieve optimal performance. The blades would be feathered into the wind to facilitate self starting in low wind conditions. Centripetal force would then increase the angle of incidence to reach optimal performance and decrease the angle of incidence in high wind conditions to minimize damage to the rotor and blades.

The researchers field tested the PPC using a Skystream 3.7 turbine as a control. The tests showed that the prototype started more easily in low wind conditions than the Skystream. However structural and mechanical failure of the prototype prevented it from achieving rated rotational speed under any wind condition. Whereas the Skystream ramped up to 300 rpm, the prototype did not exceed 100 rpm. Technical difficulties further hindered the research team, as it was unable to collect power generation data for the prototype. The researchers abandoned proposed noise studies due to their inability to collect power data. The researchers intend to continue pursuit of this technology by redesigning the PPC using nonlinear springs and other design improvements to prevent early rotation and fatigue.

Keywords: Wind turbine system, wind energy system, passive pitch control device,

forward swept blades, tip vortex shedding, speed governor

2.14.2 Introduction

Wind turbines have begun to be more widely used in providing renewable energy. Most of the applications have been large scale and predominantly in sites with a wind power Class 4 or

higher.[20] Large scale turbines use active servo-controllers to adjust blade pitch during operation to optimize efficiency in varying wind conditions. However this technology is cost prohibitive for small wind turbine applications, which instead typically rely on fixed blades. Currently most small wind turbines are designed to operate in areas rated Class 3 and above. Although some commercial small turbine manufacturers claim that passive pitch control is provided through elastic twist of the blade, the pitch variation only ranges from one to three degrees at the blade tip. To achieve optimal performance in off design wind conditions and facilitate self starting at low wind speeds, a blade pitch of 30 to 60 degrees would be required.

The researchers proposed to integrate a passive pitch control (PPC) device comprised of a camshaft with groves for balls to move in a helical path, a ball bearing outer race with cage, a torsion tension spring fixed to the camshaft, and a supporting stationary cylinder (Figure 13). Centripetal force would cause the blades to move from their starting position (Position A, Figure 14) with the blade leading edge feathered into the wind direction to a more normal orientation at design wind speeds (Position B, Figure 14). At high wind speeds, the PPC device would reduce the angle of incidence and resulting air load to minimize potential damage to the rotor or blades (Position C, Figure 14). The researchers modified their original camshaft design several times due to structural failure and installation and design errors. They replaced the ball in groove configuration with a pin in slot mechanism. They also redesigned the prototype rotor assembly, originally designed for counter clockwise rotation, to accommodate the clockwise rotation required by the hub. In spite of design modifications, the PPC failed due to inadequate spring stiffness that allowed the rotor blade to prematurely compress, bringing the blade back to the starting position. The researchers also proposed to conduct blade design analysis and to design a cogging torque free generator, but scaled back the project objectives due to design complications and cost concerns. The researchers conducted testing of the prototype using a commercially available Skystream 3.7 small turbine as a control. Although they collected power generation data for the control, technical difficulties prevented collection of data for the prototype. Consequently, they did not perform planned noise studies.

If wind turbines could be designed to harvest wind power in Class 1 and 2 areas, the researchers estimated that California has the potential to generate 5 to 20 percent more energy from its wind resource than is possible using current technology.

20 American Wind Energy Association (AWEA), "Basic Principles of Wind Resource Evaluation" (1996). http://www.awea.org/faq/basicwr.html

Figure 13: Prototype Hub with PPC Devices

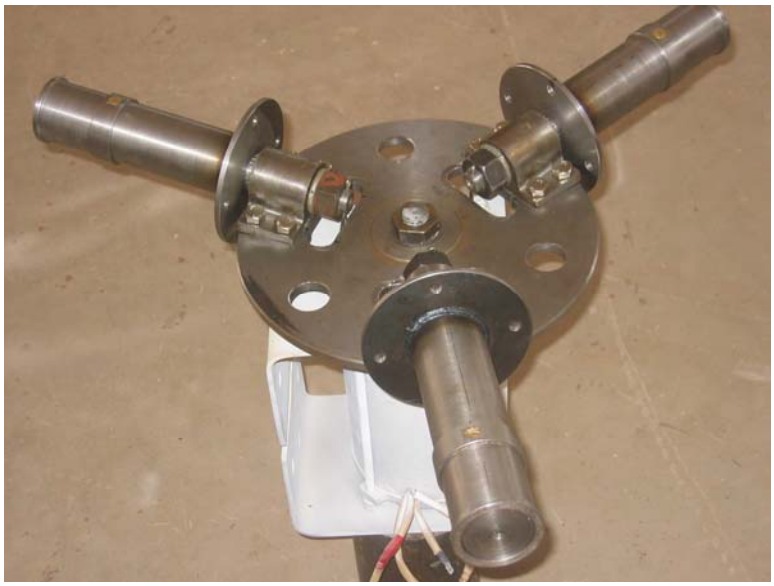
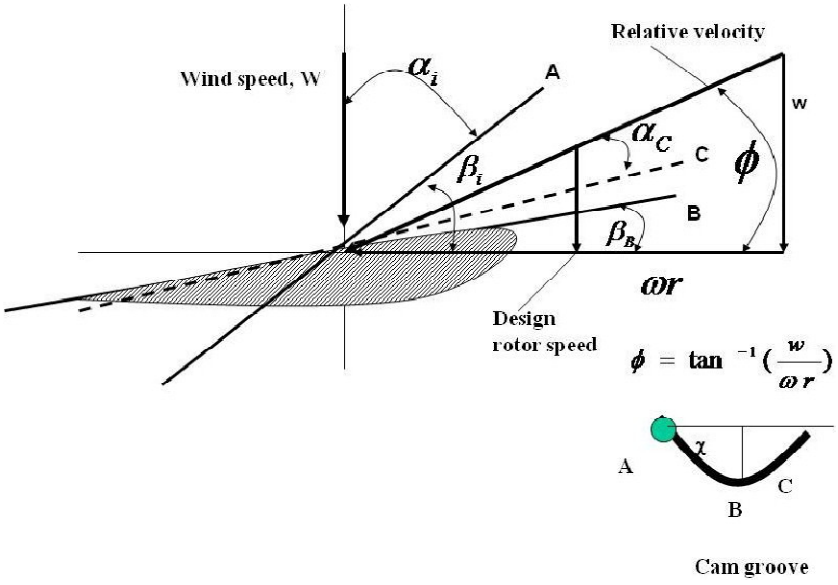


Figure 14: Schematic Diagram of Blade Setting and Cam Groove



2.14.3 Objectives

The goal of this project was to determine the feasibility of designing small wind turbines that can passively pitch their blades for maximum energy production in all wind speed conditions while being environmentally and aesthetically appealing. The researchers established the following project objectives:

1. Document design specifications.
2. Fabricate and bench test a passive blade pitch control device for functional objectives and optimal blade setting with respect to wind speed.

3. Fabricate three blade test articles having the following leading edge configurations: straight, swept back, and swept forward. Conduct IEC norm strength and vibration tests.
4. Fabricate a cogging torque free generator.
5. Discuss the parameters to be sensed and recorded for power and noise performance evaluation with test engineers.
6. Conduct field tests and verify intermittent data to see whether any parameters are to be varied.
7. Evaluate the performance of the prototype wind turbine with respect to:
    a. Annual energy production increase by 5 percent or better
    b. Noise level reduction by 5 decibels or better
    c. Annual energy cost less than 7 cents/ kWh

2.14.4 Outcomes

1. The researchers conducted MATLAB design calculations and created CAD drawings for the PPC and the blades. The CAD drawing included rolling balls along a cam groove. The researchers did not include calculations in the final report.
2. The researchers fabricated several PPC models. Based on field testing of these models, several design modifications are needed.
3. The researchers fabricated a forward swept blade conforming to an elliptical shape. After field testing of this blade, they modified the forward swept blade design to conform to a parabolic shape which has a more subtle curvature. They did not fabricate swept back and straight configurations. The researchers did not perform norm strength and vibration testing.
4. The researchers determined that the Skystream 3.7 generator matched their desired specifications, and they procured two of these wind turbines for use as the control unit and the prototype unit. The prototype unit consisted of the procured turbine with the rotor replaced.
5. The researchers prepared a test plan to measure power and noise in a side by side comparison at the Alternative Energy Institute (AEI).
6. The researchers performed three field tests. The first field test included the ball in groove PPC prototype. This test failed because the prototype rotor was designed to rotate in the opposite direction required of the Skystream hub. Mechanical failure led to redesign of the PPC using the pin in slot configuration. The second field test with the redesigned PPC failed during installation. The rotor fell from the tower, damaging it irreparably. The third field test included a pin in slot PPC. The production Skystream (control) ramped up to 280 to 300 rpm, but the prototype remained at approximately 60 rpm, regardless of the wind speed. On the second day of the third field test, the

researchers noted that the control was stationary, but the prototype was still rotating under very low wind conditions. They collected power generation data for the control, but they did not indicate power output for the prototype. The researchers noted in the technical review reply that the data collection failure was due to faulty wiring, but subsequent testing confirmed that the prototype could produce power up to 724 watts in 13 m/s wind. Inspection of the prototype after the third field test indicated that premature compression of the spring led to stalling of the rotor, preventing it from attaining rated speed. Qualitative results from field testing include:

a. The PPC device was able to control the rotor speed in varying wind speeds.

b. Forward swept blades showed easy starting under low wind conditions.

c. The rotor fitted with PPC devices and forward swept blades exhibited smooth and balanced operation.

7. Since the researchers did not obtain operational data from the prototype, they could not make comparison assessments.

2.14.5 Conclusions

1. The researchers met the objective to document design specifications, at least graphically, for two design iterations tested and one design iteration proposed. Although the researchers' design focused on functionality, lack of focus on durability and mechanical stability was evident during field trials. The researchers acknowledged the need for improvements in these areas.

2. The researchers met the objective to fabricate and bench test the PPC device for functional objectives and optimal blade setting with respect to wind speed. Bench testing led to the first design iteration where cam followers were replaced by rolling balls.

3. The researchers did not meet the objective to fabricate and test three blade configurations. Elimination of the straight configuration was based on the researchers' observations of an unrelated installation in India rather than on test data for the proposed study. The swept back configuration was not fabricated, but purchased as part of the control turbine. The researchers did not address the implications of multiple independent variables between the control and prototype:

   a. Control used swept back blade configuration and prototype used swept forward blade configuration.

   b. Control used fixed blades and prototype used PPC device.

   Although the researchers noted a simplification in the fabrication process, they did not include scientific justification for selection of the parabolic over the elliptical configuration of the forward swept blade. Had the field testing been successful, it would have been difficult to isolate the contribution of the blade design from the PPC device.

4. The researchers noted that the field test site was changed from National Renewable Energy Laboratory to AEI, which did not require norm strength and vibration testing of

the blades. However inclusion of this testing might have been appropriate, given that they neither proposed nor performed other strength or safety testing. The project objectives section notes, "The research team ensured adequate strength reliability by using a high number of woven glass fiber and high density polyurethane foam (PUF) cores." However the team performed no analysis to support this claim.

5. The researchers did not meet the objective to fabricate a cogging torque free generator. Rather, they procured commercial generators. Although the Skystream 3.7 matched required specifications, those specifications were not detailed in the report.
6. The researchers met the objective to prepare a field test plan.
7. The researchers did not meet the objectives set forth for field testing. They did not obtain quantitative data for analysis, and field observations were insufficient to support the qualitative conclusions.
    a. Although wind speeds varied, as evidenced by variation in rotor speed for the control, the prototype did not exceed 100 rpm. Observation of the PPC at the completion of the test indicated that the spring compressed prematurely, rotating the blades to the start up position rather than one optimal for the given wind speed.
    b. This conclusion is based on a single observation.
    c. Although the researchers noted the rotation was smooth and well balanced, the observations were made at 100 rpm and are not necessarily applicable to operation at rated speeds three times that observed.
8. The researchers did not meet the objective to do a comparative analysis between the control and prototype due to lack of data acquisition.

2.14.6 Recommendations

The researchers were unable to achieve their project goal due to significant design, mechanical, and installation issues. The researchers recognized "plans to develop a novel blade shape and a novel generator may have diverted resources away from the main focus of the project – the PPC device." The concept of PPC shows great promise for small wind turbines and seems a natural and economical extension of the technology used for large scale commercial turbines. The researchers intend to pursue design modifications to prove feasibility of this technology. They have connections to manufacturing resources capable of fabricating the PPC device for prototyping and testing.

As part of continued development of this technology, the Program Administrator recommends that the following tasks be completed:

1. Conduct redesign and testing to prevent early compression.
2. Perform strength and fatigue testing on PPC device to reduce the probability of mechanical failure.

3. Conduct field testing using identical blade configurations on control and prototype rotors to evaluate the improvement in power generation resulting from the PPC device.
4. Complete the comparative analysis proposed in Objective 7.
5. Prepare a cost/benefit and life cycle analysis for the PPC device.
6. Identify potential commercialization partners.

2.14.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. Conclusions based on field testing in this project are insufficient to quantify the benefits to California. Since a power curve for the new rotor has not yet been established, hypothetical examples must be used to estimate benefits. Theoretically, the new technology rotor is expected to provide 5-20 percent increase in energy production. At a site where the annual wind speed is 5.5 m/s, the estimated monthly energy production may be around 400 kWh. Assuming the net value of this energy (retail price of energy minus the operation and maintenance cost) is around $0.20/kWh, the yield would be about $80 per month. If the performance of a new technology rotor increased the energy production by 5 percent to 420kWh per month under the same conditions, the yield would be an additional $4 per month, totaling an additional $960 over the estimated 240 month lifespan of the turbine. Assuming a discount rate of 3 percent, this equals a net present value of about $723. An increase of 20 percent in energy production would yield a net present value of $3615. The researchers estimated the additional cost of three PPC devices to be less than $120 for a 2 kW turbine and the blade cost should be the same. Hence the new technology rotor is expected to provide a net increase in value approximately 6-35 percent of the total installed cost of the turbine (assuming $5000/kW).

2.14.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.14.8.1 Marketing/Connection to the Market

The researchers did not perform a market analysis by the end of this project. Since the project technology is applicable to all small wind turbine facilities, there are many opportunities for market connection.

2.14.8.2 Engineering/Technical

The researchers planned to revise the PPC design to include non-linear pneumatic springs. Design iterations will address the functionality and fatigue issues identified through field testing.

2.14.8.3 Legal/Contractual

The researchers performed a professional patent search. At the conclusion of the project, one US Patent application 20070207033 was pending. The researchers have secured the following patents: 5887828; 5921506; 6190484 B1; 6127739; 6278197B1; 6375127; and 6492743.

2.14.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

Because of technology immaturity, the researchers did not pursue these plans during or shortly after the project period.

2.14.8.5 Production Readiness/Commercialization

The researchers plan to pursue commercialization and have identified distributors who wish to market the PPC.

2.15 Economical Two-Axis Carousel Tracker for Concentrated PV Power Plants

Awardee: Green Volts, Inc.

Principal Investigator: Bob Cart

2.15.1 Abstract

The purpose of this project was to investigate the feasibility of a carousel style solar tracker with centralized aiming control for use in concentrated photovoltaic (CPV) power production. The intended highly accurate, dense aperture system and associated reduction in first cost and maintenance requirements would improve the competitiveness of solar installations against traditional generation alternatives. Although testing was carried out indoors rather than the originally proposed outdoor environment and the tracking accuracy specification was reduced based on expected better light focusing optics, the project was largely successful. A first prototype yielded significant areas for improvement, and a second prototype performed far better, although it did not meet the tracking accuracy specification. The research has pointed the way for further development of the tracking and optical systems and commercial applications are beginning to appear.

Keywords: Concentrated (or concentrating) photovoltaic, dense aperture, two axis, tracker, carousel, solar

2.15.2 Introduction

Despite significant and ongoing efforts to reduce the costs of photovoltaic (PV) systems, their currently projected costs do not yet provide a clear advantage over traditional generating alternatives. This remains a deterrent to the level of widespread PV deployment envisioned in California's energy policy. Further, the limited roof area available for solar installations on buildings and the land use impacts of large scale solar installations constrain the amount of energy that can be recovered at a given site. In most cases subsidies are required to bring PV system costs into parity with conventional alternatives in today's market.

One approach to improving PV economics and land impacts is use of concentrating photovoltaic technologies (CPV). By using mirrors or lenses to focus sunlight onto small, highly efficient cells, these systems produce significantly more power for a given collector area. However they require a highly accurate tracking system to ensure the array aligns precisely with the sun each day. Tracker cost, accuracy, and reliability represent continuing challenges in CPV development.

Reducing costs to a more competitive level can increase penetration of PV alternatives, bringing environmental benefits and reduced fuel price and supply risks to more California ratepayers. Increasing the efficiency of the solar array through CPV technologies can yield more energy for a given installation, potentially leading to reduced overall costs and less surface area required for equivalent output from the collectors. Both will help California realize its vision of a more sustainable energy future and will free public funds for deployment in other initiatives, such as energy efficiency.

The researchers proposed to design, build, and test a two axis carousel style solar tracker (Figure 15) with centralized control[21] to help enable economical CPV solar power production. In contrast to typical pole mounted trackers, use of a flat ground level carousel was intended to reduce the foundation and wind loading requirements for the tracker. This would lead to a need for less robust motors and gearboxes and allow use of lower cost sheet metal components. The researchers measured tracking accuracy and mechanical reliability in an indoor environment.

21 The carousel rotates with the sun's movement to provide tracking along the horizontal (x) axis and the vertical d axis (y) is provided by rotating the mounting racks up or down.

Figure 15: Second Prototype without Solar Cells Attached

2.15.3 Objectives

The goal of this project was to determine the feasibility of a unique design[22] solar tracker for concentrating photovoltaics (CPV). The project objectives and their associated performance metrics are summarized as follows:

1. Confirm that each prototype will support 6.75m^2 of concentrator aperture, assuming no shading at 30 percent sun elevation.
2. Confirm that the trackers support aperture per unit land area of greater than 20 percent.
3. Show that a single controller operates both prototypes.
4. Demonstrate the test stand is capable of measuring the actual sun position and each tracker's position within an error of +/- 0.01 degrees in different light, wind, and temperature conditions.
5. Demonstrate sun pointing accuracy within error of +/- 0.05 degrees.
6. Demonstrate parasitic loss from motors less than four watt hours per day per tracker.
7. Demonstrate the device can operate at least 500 hours without failure.
8. Confirm from the project findings projected manufacturing cost of $125/m^2 of module aperture continues to be supported.

22 Although the PI refers to the carousel tracker as a unique design, the basic principle of a horizontal rotating tracker (carousel) is well known, and there are competing offerings of such a product. See, for example, www.jxcrystals.com

9. Confirm from the project findings that projected annual maintenance cost of 5 percent of installed tracker cost continues to be supported.

2.15.4 Outcomes

1. A redesign allowed each of the two prototypes to support 11 m^2 of concentrator aperture, well above the targeted 6.75 m^2.
2. The larger design yielded an aperture per unit land area greater than 40 percent, compared to the targeted 20 percent.
3. The researchers decided not to operate both prototypes as a single unit as originally targeted for the project. This was done to allow lessons learned from testing a first prototype to be used in designing the second one.
4. The researchers did not build a test stand as originally proposed. As an alternative they attached sensors to each tracker to measure tracking accuracy. This work was carried out indoors, instead of the originally proposed testing under varying wind and temperature conditions.
5. The originally targeted sun pointing accuracy of +/- 0.05 degrees was changed to +/- 1.0 degree by the researchers during the project. They reasoned that an updated design for the optical system no longer required the original degree of precision in the tracker.
6. The prototypes met the targeted parasitic loss for the motors.
7. Neither prototype met the targeted 500 hours of operation without failure. The testing was conducted indoors rather than outside. The second prototype performed better as redesigns were incorporated.
8. The researchers estimated that manufacturing costs would be roughly \$162/m^2 of aperture at a volume of 3,500 trackers. This cost is above the targeted \$125 /m^2 of aperture.
9. The researchers indicated that while nothing was found in the project that would contradict the assumed annual maintenance cost of 5 percent of installed tracker cost, further long duration testing could provide more clarity on this target.

2.15.5 Conclusions

The project largely met its objectives and identified a reasonable path for further research and development to address those that were not met. It appears that subsequent to this project the researchers successfully demonstrated more advanced prototypes, secured significant venture capital funding, entered into a power sales agreement with a California utility for a 2 megawatt plant, and began offering product for commercial sale.

1. The redesigned tracker led to improved results for both Objectives 1 and 2. This suggests it was a good decision to trade off potentially more difficult fabrication and mechanical design for lower overall cost/unit aperture and higher aperture per required land area.
2. See Conclusion 1 above.

3. The decision to control and test the first prototype, then use lessons learned to improve a second unit provided significant improvement in tracker performance. Although neither prototype met the targeted tracking accuracy, accuracy improved from roughly +/- 16 percent on the first unit to +/- 3 percent on the second.

4. The test data using sensors attached to the panels in lieu of the originally proposed test stand appeared to be adequate for the project. However conducting all testing indoors compromised the objectives of demonstrating operation under varying wind and temperature conditions. The researchers acknowledged this in the final report and indicated outdoor testing would be a high priority in future research and development.

5. The change in the tracking accuracy target was enabled by improved optical system design according to the researchers. However there is no supporting information about the improved design and it is not possible to assess whether an overall system with the improved design but lower accuracy is comparable to what would have been achieved with the original tracking accuracy.

6. The motors performed as expected, and the researchers' conclusion that further work to reduce parasitic load may not be justified appears appropriate.

7. Early failure of the prototypes was accompanied by significant learning about its causes and is likely to lead to more robust designs in future research.

8. Use of a sheet metal design for the tracker was innovative and has the potential to lead to lower cost than for other designs. However it is not possible to assess the robustness of the researchers' estimated manufacturing costs, since no supporting documentation or detail was presented.

9. Without serious long term testing under outdoor conditions, it is not possible to project maintenance costs with any degree of confidence. The researchers acknowledged this and flagged this for further research.

2.15.6 Recommendations

This project provided a sound foundation for continued development of the researchers' proposed carousel tracker and associated concentrating optics. Based on current information, it appears most of the necessary research to bring a product to market has been successfully completed, although the researchers did make a case for further research funding in support of proposed long term testing of a 30 kW installation. This testing would be helpful in ensuring a commercially viable product.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program. Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.15.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research would be reduced environmental impacts of the California electricity supply. Assuming the research leads to the stated goal of a system which is truly cost competitive with traditional generation, improving the economics of solar energy systems would increase their market penetration, accelerating California's transition from a electricity generation mix with significant quantities of carbon based fuel generation to a cleaner, more sustainable set of technologies.

2.15.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.15.8.1 Marketing/Connection to the Market

The researchers announced a two megawatt power purchase agreement with Pacific Gas and Electric Company, as well as receipt of significant venture capital funds. These signal good prospects for commercial success. There are other market participants offering carousel style CPV systems.

2.15.8.2 Engineering/Technical

The largest remaining issue is long term testing to confirm performance and reliability of the system under actual field conditions. The researchers indicated this testing was underway.

2.15.8.3 Legal/Contractual

The researchers indicated there were six patents pending, although it was not clear how directly these relate to the subject of this research. A patent firm conducted a search and reported no conflicts.

2.15.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

Quality testing to confirm long term system performance and reliability is a high priority in bringing this system to market. The researchers reported there are no apparent environmental or safety issues.

2.15.8.5 Production Readiness/Commercialization

At the conclusion of this research project the design had evolved considerably but was not ready for commercial application. It appears that subsequent to completion of this research there has been considerable progress and early commercialization is underway.[23]

2.16 Hydrogen Enrichment of Landfill Gas for Enhanced Combustion

Awardee: University of California, Davis

Principal Investigator: Dr. Paul Erickson

2.16.1 Abstract

Researchers measured the effect of hydrogen enrichment of landfill gas (HLFG) on nitrogen oxides and carbon monoxide emissions, power, efficiency, and lean operating limit on a normally aspirated landfill gas fueled spark ignition engine. In this investigation the researchers modified a 0.745 liter two cylinder Kawasaki engine and operated it with simulated landfill gas containing four different levels of hydrogen concentrations. The researchers compared the generated data with modeling predictions from three engine predictive models. Constant revolutions per minute (rpm) empirical results showed NO_x emissions could be lowered to the anticipated future best available control technology (BACT) requirements for landfill gas to energy projects of 0.20 g/kWh with 40 percent hydrogen enrichment, while retaining 95 percent of the baseline power and keeping CO emissions under 630 parts per million (ppm). Of the three simulation models tested, only WAVE yielded good correlation with the experimental data for HLFG mixtures under the operating conditions in this study. In a cost comparison, the researchers calculated that only hydrogen enrichment using an in-stream autothermal fuel reformer had the potential to be more cost effective at reaching the NO_x reduction targets than current strategies.

Keywords: Hydrogen, LFG, landfill gas enrichment, bi-fuel, emissions, spark ignition, NO_x, CO, burn rate

2.16.2 Introduction

Nearly 1 percent of California's electricity is produced by burning landfill gas, primarily in internal combustion engine generators. Landfill gas (LFG), produced by decomposing buried municipal solid waste, is approximately 60 percent methane and 40 percent CO_2. It is frequently captured and often flared to convert methane to CO_2. Methane has 21 times the greenhouse gas potential of CO_2, and flaring thus reduces effective greenhouse gas emissions. To further reduce greenhouse emissions and to recover energy and produce electricity, landfill operators increasingly burn LFG in modified internal combustion (IC) engine generators, microturbines,

23 http://www.greenvolts.com/category/news_and_events/news/

and boilers. Regulations demanding lower NO_x emissions (up to 90 percent reduction for some applications) are major barriers to new landfill gas to energy (LFGTE) projects. While some power plant operators are meeting current NO_x regulations with after treatment processes such as selective catalytic reduction (SCR), these catalysts are expensive, easily poisoned by trace amounts of sulfur present in LFG, and may not meet proposed future standards.

Hydrogen enrichment of compressed natural gas (HCNG) is a technology currently being used to lower NO_x emission rates in IC engines and has been proposed for landfill gas fueled engines. Hydrogen has favorable combustion characteristics which may enhance flame stabilization when mixed with other fuels in small percentages. Thus in natural gas engines, hydrogen enrichment can allow the use of lean burn or high charge dilution strategies to cool combustion, drastically reducing NO_x production rates and potentially eliminating the need for an after treatment catalyst. Senate Bill 1298 (2000) requires that the best available control technology (BACT) emission level of NO_x for distributed generation units meets the same level as a central station power plant equipped with BACT at the earliest practicable date.

Although much experimental and analytical work has taken place on the subject of hydrogen enriched natural gas and basic landfill gas combustion, there is little work to predict and validate the behavior of hydrogen enriched LFG in IC reciprocating engines such as those used in many LFGTE projects. In this project researchers proposed and evaluated a strategy of enriching landfill gas with hydrogen to allow high air/fuel ratios that allow significant reductions in NO_x while maintaining low CO and hydrocarbon (HC) emissions. The researchers also evaluated predictive modeling approaches for such engine application.

2.16.3 Objectives

The goal of this project was to determine the feasibility of using hydrogen enrichment to enhance landfill gas combustion in stationary internal combustion (IC) reciprocating engines. The researchers established the following objectives:

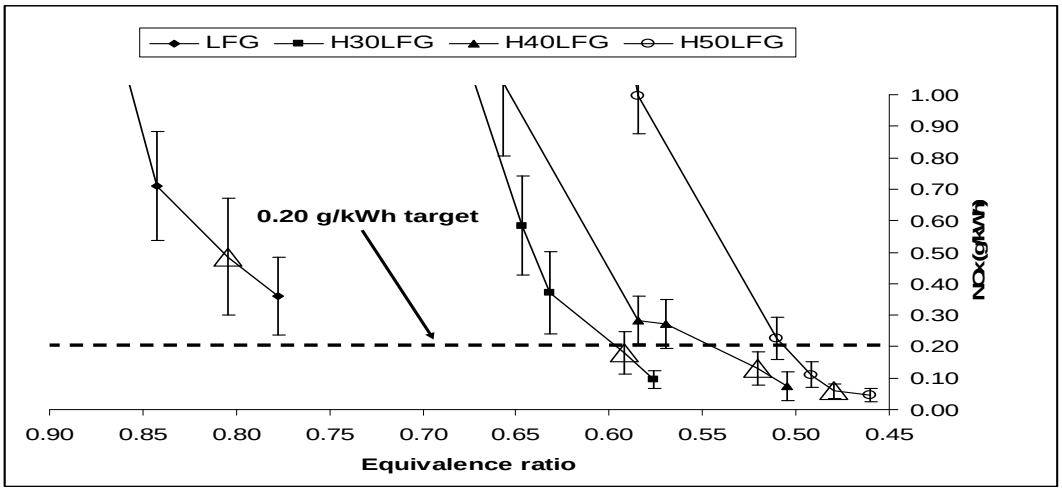
1. Develop and validate an analytical model to predict the relationship between hydrogen enrichment, lean limit, thermal efficiency, and NO_x emissions.
2. Verify the hydrogen enrichment scheme in a small scale engine/generator using simulated landfill gas. Metrics of success included:
    a. Engine out NO_x and CO emissions low enough to meet Senate Bill 1298 standards.
    b. Thermal efficiency greater than or equal to current technology.
    c. Levelized cost of electricity equal or less than current LFGTE projects.
    d. Emissions and lean limit of hydrogen enrichment predicted within 0.5 percent of actual.
    e. Hydrogen enrichment application demonstrated on a small system.
3. Predict performance and cost for full-size systems using different hydrogen production and supply strategies.

2.16.4 Outcomes

1. The researchers compared the predictions of three computer simulations (one proprietary model, CHEMWORK_6, and WAVE) with the measured NO_x levels under different concentrations of methane and hydrogen. They found only WAVE correlated well with measured outputs.

2. The researchers modified a two cylinder 0.745 liter liquid cooled fuel injected Kawasaki engine to run on simulated LFG and hydrogen. Thus hydrogen enrichment of simulated landfill gas was successfully demonstrated on a small internal combustion engine. Hydrogen enrichment allowed for a 1.5 percent increase in thermal efficiency over current technology. Researchers made test runs using a range of hydrogen enrichment levels (20-40 percent) measured relative to the methane content and took NO_x and CO measurements. They did not measure hydrocarbon emission levels, also subject to increasingly stringent regulatory standards. Calibrated mass flow controllers allowed known fuel mass flow rates to enter the engine. An oxygen sensor allowed calculation of the equivalence ratio based on stoichiometry. Researchers controlled timing via an electromotive ignition system. They used a water break dynamometer to provide the load. Figure 16 shows the measured NO_x results. Hydrogen enrichment of 40 percent by volume met SB1298 standards for NO_x emissions in the particular engine tested. Analytical models proved accurate to within 25 percent of measured NO_x emissions with proper curve fitting for heat release

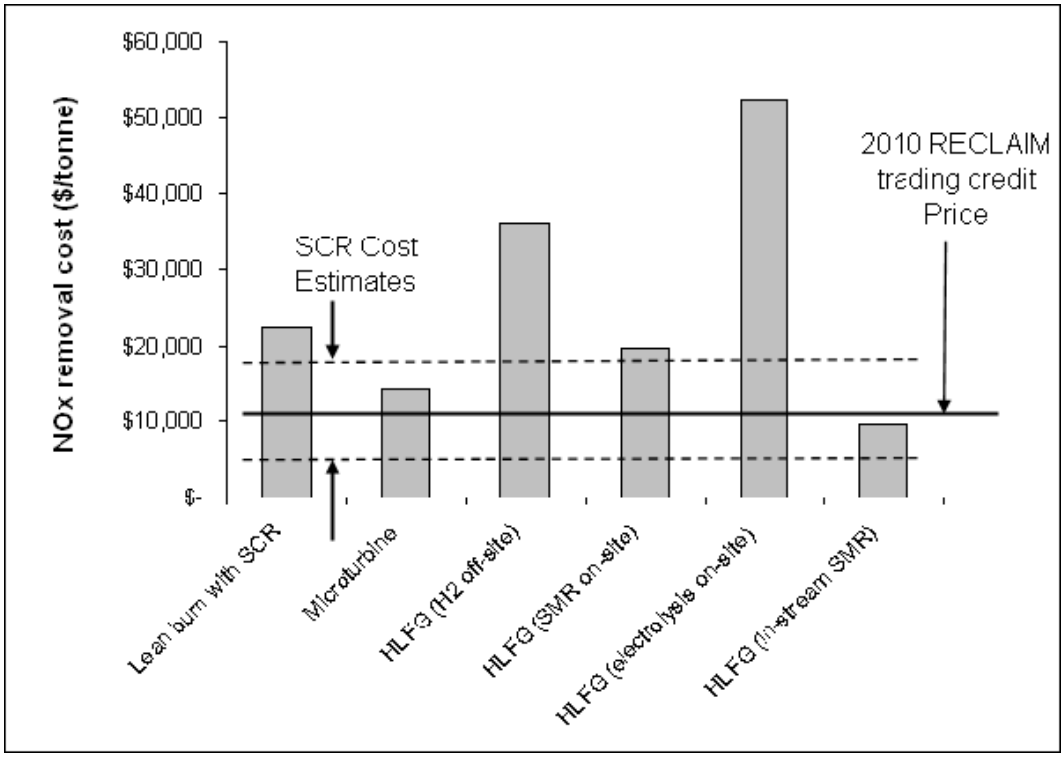
Figure 16: NO_x Emissions of HLFG under Different Hydrogen Enrichment Ratios



3. The researchers calculated the comparative cost of generation from hydrogen enriched landfill gas using various NO_x reduction schemes. They investigated seven cases with a lean burn reciprocating engine with no after treatment as the baseline (Case 1). Case 2 was a LFGTE plant incorporating lean burn with selective catalytic reduction (SCR). Case 3 was a LFGTE plant using microturbine technology. Case 4 incorporated hydrogen enrichment technology (HLFG) with hydrogen delivered from an external

source and stored on site. Case 5 was a HLFG system with hydrogen produced on site from a steam methane reformer (SMR) with a separate natural gas (NG) source. Case 6 was a HLFG system with hydrogen produced on site from an electrolyzer powered with electricity from the grid. Case 7 was a HLFG system with hydrogen produced from part of the LFG by an autothermal SMR mounted in the fuel stream. Figure 17 shows the results. Total levelized cost for the HLFG with an in-stream autothermal reformer is the least expensive option for significant NO_x reduction.

Figure 17: Calculated Comparative Cost of Electricity for Different Methods of Power Generation



2.16.5 Conclusions

The researchers demonstrated the technical feasibility of using hydrogen enrichment to lower NO_x emissions of LFG used in internal combustion engines. The results from this study demonstrate that with an appropriate level of hydrogen enrichment IC engines can meet NO_x emissions specified by Senate Bill 1298 for LFG combustion.

Of the three simulation models, only one provided good correlations with measured results and that only with low equivalence ratios. Data did not achieve the desired accuracy of 0.5 percent. The results showed an accuracy of 0.5gNO_x/kWh at low equivalence ratios. The researchers accomplished experimental validation of HLFG on a small scale IC engine using simulated LFG. The results demonstrated that with a suitable level of hydrogen addition, NO_x emissions specified for LFG combustion of 0.2 grams per kilowatt hour can be met with hydrogen enrichment of at least 40 percent. The research showed thermal efficiency of the engine to be

slightly higher than current technology while not increasing CO emissions significantly above baseline. However when thermal efficiency of hydrogen production was considered, the result was a lower overall process efficiency as compared to the lean burn ICE engines.

Finally, the research showed the levelized cost of electricity using SMR of the LFG stream was potentially cost competitive with current technologies for LFG utilization.

2.16.6 Recommendations

The researchers should investigate hydrogen enrichment in larger IC engines and in other prime movers, such as combustion turbines, that may be applicable to the larger landfills in California. This should involve actual running tests. The researchers should also determine the cost and performance (efficiency and cost) of using hydrogen enrichment with a wider range of methane content (landfills in California have methane ratios of 10 to 60 percent) than investigated in this study. The researchers should implement a rigorous test program for the in-stream autothermal reformer and complete a comprehensive life cycle analysis. The researchers should develop an empirical model of prime mover performance and emissions as functions of hydrogen enrichment levels and LFG composition. The latter would be crucial for engine mapping for control purposes and ultimate commercialization.

The researchers should develop cooperative testing and development arrangements with the major engine manufacturers and, contingent upon the prime mover tests noted above, with micro-turbine manufacturers. As part of that process, emissions certification should begin.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.16.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is from reduced environmental impacts of the California electricity supply system. Ancillary benefits arise from reduced impacts of transmission system expansion by allowing for greater use of distributed generation.

According to the California Air Resources Board (CARB) Greenhouse Gas emissions inventory, landfills emitted 300,526 metric tons of methane or the equivalent of 6.3 million metric tons CO_2 in 2006.[24]

Converting landfill methane into electrical energy has the potential to reduce CO_2 equivalent emissions by nearly six million metric tons per year. By way of comparison, the 20 percent renewable portfolio standard[25] is expected to achieve an eight million metric ton reduction.[26] The clean use of landfill gas proposed in this project could contribute as much as 75 percent of the greenhouse gas emission reduction as a 20 percent contribution of renewables and with lower costs.

2.16.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.16.8.1 Marketing/Connection to the Market

The researchers have established connections to potential users of the technology, including landfill operators, dairies, and wastewater facility owners. Initial discussions and conference presentations in 2006 spurred some interest in this technology. Engine manufacturers have also expressed initial interest pending results of larger engine demonstrations.

2.16.8.2 Engineering/Technical

The EISG Program Administrator is not aware of any ongoing technical work related to this project after the completion of this project.

2.16.8.3 Legal/Contractual

The researchers have not applied for patent protection nor reached development agreements with engine manufacturers.

2.16.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

There are no known or anticipated environmental or safety risks associated with the technology. There may be performance quality issues associated with the in-stream reformer for hydrogen production. The researchers should develop performance quality plans to account for the wide variety of gas compositions associated with waste streams.

---

24 http://www.arb.ca.gov/app/ghg/2000_2006/ghg_sector_data.php

25 The CARB has not provided estimates of the GHG emission reduction of the 33 percent RPS, established in Executive Order, in the scoping plan.

26 http://www.arb.ca.gov/cc/scopingplan/sp_measures_implementation_timeline.pdf

2.16.8.5 Production Readiness/Commercialization

Development of production readiness and commercialization plans is premature until technical issues are successfully addressed.

2.17 Phase Change Material (PCM) Solar Thermal Storage System

Awardee: Santa Clara University

Principal Investigator: Jorge E. Gonzalez

2.17.1 Abstract

The goal of this project was to demonstrate the technical and economic feasibility of solar thermal storage using a phase change material (PCM). Researchers analyzed three PCMs exhibiting a melting temperature between 80 ^{O}C and 100 ^{O}C for use in solar thermal air conditioning systems. The researchers selected the lowest melting temperature PCM, RT-80, for further analysis as a composite PCM (CPCM) using 68 and 95 percent by volume of compressed expanded natural graphite to optimize the thermal properties of the PCM matrix. The researchers used numerical modeling, calibrated using laboratory testing results, to further optimize the CPCM.

Researchers constructed a prototype thermal storage tank to deliver one refrigeration ton of cooling load for four hours of operation. The latent heat storage provided by the PCM allowed a 56 percent volume reduction in comparison with a similarly rated sensible (water) heat storage tank. Preliminary cost estimates indicated that a latent heat (PCM) storage tank would be similarly priced to a sensible heat (water) storage tank. This would be true because the increase in material costs for the PCM material would be counteracted by the decrease in tank costs given the reduced size requirement for a given heat storage capacity. Thus the primary benefit in PCM thermal energy storage is to accommodate applications with space restrictions, including small to medium sized residential and commercial buildings.

Keywords: PCM, composite PCM, solar thermal storage, absorption cooling system, heat transfer rate, paraffin and graphite, latent heat, volume reduction

2.17.2 Introduction

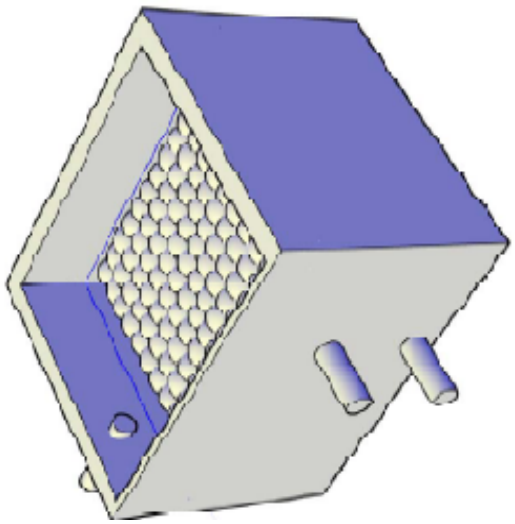
Water heating and air conditioning systems account for 28 percent of energy usage in the residential sector and 16 percent of energy usage in the commercial sector. Solar energy advances in this area have been limited due to a lack of reliable technologies that can deliver a high inlet fluid temperature, adequate thermal storage, and provisions for incorporation of the technology into the building system. Solar adsorption systems are hindered by their inability to operate outside of daylight hours and by their size requirements.

The researchers in this project incorporated phase change materials (PCM) into a solar adsorption storage unit to increase operational hours and to reduce size requirements of the

system for a given thermal storage capacity. They selected and analyzed PCMs for melting temperature, thermal conductivity, and suitability for use within a thermal storage tank. They developed a scaled down prototype based on numerical modeling results to assess the benefits of incorporation of PCMs and composite PCMs into a thermal storage tank as shown in Figure 18. For a commercial installation, the researchers found that the storage tank size could be reduced by approximately 50 percent and deliver the same thermal capacity for essentially the same cost as a similar capacity tank using water as the medium. The increased material cost of the PCMs was counteracted by the decreased tank cost due to its smaller size.

In residential and smaller commercial installations where size constraints are significant, usage of PCM solar thermal storage systems could lead to increased adoption of solar energy as an alternative renewable energy source. This could lead to potential annual energy savings of about 12 kWh/ft^2 in California. This technology could also be expanded to accommodate use in heating systems.

Figure 18: Integration of PCMs in a Large Storage Tank Enclosed in a Copper Tube or Spherical Container



2.17.3 Objectives

The goal of this project was to demonstrate the technical and economic feasibility of solar thermal storage with PCM for high temperature applications by constructing and testing a prototype unit and determining the optimal size, materials, and price of a commercial unit. The researchers established the following project objectives:

1. Manufacture a PCM matrix with a composition of 60-80 percent by weight of paraffin, thermal conductivity higher than 40 W/m-K, and paraffin latent heat not reduced more than 20 percent.
2. Develop a thermal and computational model for storage energy with phase material. Size and material optimization of the prototype design is to be based on parametric

analysis of the thermal performance of the tank in California using the thermal simulation code.

3. Set up a scaled down prototype unit for experimental purposes. Size is to be not larger than 100 gallons per cooling ton for absorption technologies. Conduct tests. Thermal capacity is to increase by more than 50 percent over conventional water storage systems for same capacity.

4. Generate a full report on final cost demonstrating commercial feasibility of the system. Complete final construction for a compact unit at a cost 25 percent higher than water. Payback for a solar A/C with PCM storage tank should be reduced by two years. Generate a full report on manufacturability of the tank.

2.17.4 Outcomes

1. The researchers considered three PCMs for use based on a melting temperature range from 80 OC to 100 OC. CSX micro-crystalline wax exhibited the highest storage capacity, but was eliminated due to lack of technical data. Instead, the researchers chose RT-80 for prototype development. They incorporated compressed expanded natural graphite (CENG) into the matrix to increase thermal conductivity of the PCM. They prepared two samples with 95 percent by volume or 83.5 percent by weight (CPCM1) and 68 percent by volume or 65 percent by weight (CPCM2). The researchers analyzed the PCM and both composite PCM samples for heat flow characteristics, specific heat capacity, latent heat, and thermal conductivity. Thermal conductivity for the PCM, CPCM1, and CPCM2 were 0.2, 0.7, and 1.2 W/m-K, respectively. Latent storage reductions in comparison to the PCM were 23 percent for CPCM1 and 53 percent for CPCM2.

2. The researchers used the configuration shown in Figure 19 to model a storage tank incorporating CPCMs encased in a copper tube. They presented details of the numerical model, assumptions, and boundary conditions in the final report. They calibrated the model using laboratory test results and performed parametric studies to analyze and optimize the unit size, outlet fluid temperature, heat transfer coefficient, and total solidification or melting time. Modeling results indicated a 1.5 percent and 4 percent increase in storage capacity over water tanks with a PCM volume content of 2.5 percent and 6.6 percent, respectively.

3. The researchers used numerical modeling results to design a prototype storage tank that would deliver one refrigeration ton of cooling load for four hours of operation of a water fired adsorption chiller with a coefficient of performance of 0.7. Results indicated heat storage capacity improved with an increasing concentration of PCMs. A unit with 100 percent PCM storage could be 60 percent smaller than a similarly rated sensible heat storage unit. Test and modeling results indicated that a one ton storage tank could be constructed with 83 to 95 gallons PCM. The researchers tested a scaled down 10 gallon storage tank containing a 2 inch diameter, 18 inch tall tube containing 700 grams of PCM and used this test to validate numerical modeling results.

4. The researchers prepared a rudimentary cost estimate comparing sensible and latent storage tanks. They estimated manufacture of the PCM to be 25 percent of the material

tank cost and the cost of the PCM storage tank to be $25/gallon. They estimated the cost of sensible and latent storage tanks to be $5000 and $4895, respectively. The researchers did not address manufacturability.

2.17.5 Conclusions

1. The researchers were successful in manufacturing two composite matrices of PCM and CENG in the range of 60 to 80 percent by weight, but failed to meet the performance objectives for the composites. The bases for the performance objectives were not discussed in either the proposal or the final report, but appeared to be overly optimistic.
2. The researchers were successful in developing and validating a numerical model to analyze and optimize a PCM thermal storage unit.
3. The researchers were successful in designing a full scale PCM storage device and bench testing a scaled down unit. Rather than demonstrating an increased storage capacity for a given size, the researchers held capacity constant and demonstrated the size reduction that could be realized with the incorporation of PCMs.
4. The researchers did not meet the objective to perform a rigorous cost analysis, nor did they address commercial feasibility or manufacturability. Broad assumptions allowed the researchers to present an order of magnitude estimate, without any significant granularity. Additionally, they presented simplifying assumptions without justification. Given the similarity in cost between the two systems, there appeared to be no significant reduction in payback period. They did not address manufacturability.

2.17.6 Recommendations

The researchers were successful in constructing and testing a prototype PCM thermal storage tank and intend to further improve upon their work with additional research and testing to assess the suitability of alternative PCMs, improve upon the manufacturability of the PCM composite, and investigate alternatives for encapsulation of the PCMs. Full scale testing for a period of one year needs to be performed in a residential or commercial application. The PCMs also need to be cycle tested to assess the life expectancy of the material.

The researchers adequately addressed the size constraints presented by incorporation of solar thermal systems as an alterative to non-renewable heat storage tanks, but did not address the limitation of reduced operational hours inherent in solar systems. Impacts of this limitation and resolutions should be a significant focus of future research. As part of continued development of this technology, the Program Administrator recommends that the following tasks be completed:

1. Perform a rigorous cost analysis without simplifying assumptions.
2. Investigate the benefits of peak shifting or expansion of operational hours as a result of PCM usage. Determine the limitations and ramifications of usage of a system which may not be continuously operational as a result of solar usage in lieu of non-renewable resources.
3. Perform a product life cycle analysis.

4. Investigate the environmental or health risks associated with proposed PCMs including RT-80.

5. Identify a commercialization partner.

2.17.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. The use of a solar thermal storage system could lead to adoption of solar energy for water heating and air conditioning in residential and commercial applications. The researchers estimate that a domestic hot water system could save up to 30 percent of the total energy in a home. This is estimated to be about 4 kWh^2/ft^2/year, which translates to an annual savings of more than $100M. This would also result in a carbon dioxide emission reduction of approximately 1M metric tons annually.

2.17.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.17.8.1 Marketing/Connection to the Market

Market analyses indicate that this technology is applicable to residential, commercial, and industrial sectors. Potential customers have been identified, and governmental incentive programs will increase the demand for solar based technologies.

2.17.8.2 Engineering/Technical

The researchers have not identified any engineering or technical barriers to the technology development.

2.17.8.3 Legal/Contractual

The researchers have performed a patent search and are in the process of applying for patents for the technology.

2.17.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

Regulatory barriers may surface based on the flammability of the PCM. However the researchers have proposed alternatives to address this issue. Environmental, safety, risk assessment/quality plans have not yet been prepared.

2.17.8.5 Production Readiness/Commercialization

The researchers plan to pursue commercialization and have identified potential commercialization partners, but the technology has not been adequately tested to be market ready.

2.18 Increasing the Energy Efficiency of Vapor Compression Systems by using "Smart" and Cost Effective Compressors

Awardee: Purdue University

Principal Investigator: Eckhard A. Groll and Steven D. Pekarek

2.18.1 Abstract

Heating, ventilation, and air conditioning (HVAC) consumes the most electricity of all end uses in residential and many commercial buildings. For this and other reasons, HVAC represents an important area for energy efficiency improvements. Researchers in this project improved the performance of an HVAC system and modeled energy consumption, power factor, and torque ripple for a three ton air conditioning system. They evaluated several alternative designs to minimize energy consumption over a seasonal cycle, maximize power factor, and minimize torque ripple of the motor (an acoustic noise source). The focus turned to optimizing the compressor motor's run capacitance. The researchers determined compressor run capacitance could be adjusted and could improve the compressor power factor by 15 to 20 percent with negligible impact on the real power consumption of the compressor, but with a corresponding decrease in system coefficient of performance. Utilities would benefit from an improved power factor for this end use and overall source energy consumption would be reduced, although consumers would see minimal or perhaps negative direct benefit.

Keywords: Compressor, HVAC, efficiency, optimization, power factor

2.18.2 Introduction

In 2005 California residents consumed over 9000 gigawatthours for air conditioning.[27] Adding similarly large consumption for commercial and industrial heating, ventilation, and air conditioning (HVAC) makes this end use one of the most energy and power hungry applications. Thus the goal of providing energy efficient and environmentally friendly air conditioning is crucial.

Researchers and manufacturers have long investigated ways to improve the efficiency of HVAC systems. Much of the research has focused on improving individual components of the air conditioning system, such as the compressor or the motor used to drive the compressor.

27 http://www.eia.doe.gov/emeu/recs/recs2005/c&e/airconditioning/excel/tableac2.xls

In addition to individual system components, researchers have looked at methods to vary the cooling capacity of the compressor to match the cooling load. These methods include hot gas bypass, evaporator temperature control, clearance volume control, multiple compressor control, cylinder unloading, and variable speed control. Each of these methods has distinct costs and benefits, but when comparing the overall efficiency of the different methods, variable speed operation is the choice for most manufacturers. Few of these approaches pay explicit attention to the gap between real and reactive power and the associated burdens on the utility grid.

In this project, researchers focused on the overall system operation with specific attention to closing the gap between real power and reactive power through the use of close coupled run capacitance of the compressor motor. This has the potential to provide utilities significant benefit by improved power factor for all motor loads, not just those associated with HVAC.

2.18.3 Objectives

The overall goal of this research was to create more efficient air conditioning and heat pump systems by using "smart" compressors. The researchers established the following objectives:

1. Validate a performance predictive model[28] with manufacturer performance.
2. Validate compressor model with manufacturer performance map.
3. Reduce volume and/or cost of motor by 20 percent.
4. Obtain 20 percent increase in coefficient of performance (COP).

2.18.4 Outcomes

1. The researchers developed and verified a computer model of the electrical characteristics of a single phase induction machine and a model of torque of a reciprocating compressor.

2. The researchers investigated several approaches to improve the efficiency performance of the motor/compressor combination using the computer model. This led them to focus on reducing reactive power by changing motor capacitance.

3. The researchers did not report on the volume or cost of the motor.

4. The researchers did not measure or report actual changes in COP, as their working objectives changed during the course of the project to a focus on power factor.

2.18.5 Conclusions

The researchers successfully demonstrated that varying the run capacitor improved the real power (efficiency) of the single phase induction motor in an HVAC application. The researchers also developed and verified a computer model that can be used to determine the optimal capacitance in a single home application or a broad geographic region.

The run capacitance has a tremendous impact on the reactive power, as would be expected. The researchers demonstrated that the run capacitance can be adjusted to dramatically reduce reactive power.

---

28 Purdue's air conditioning analysis software package ACMODEL

2.18.6 Recommendations

The researchers should publish their results in technical and utility trade journals. The researchers should develop documented estimates of cost, energy, and performance gains that could be expected if the power factor of residential HVAC systems increased by the 15-20 percent indicated by this research. They should investigate rate designs that incent residential consumers to improve their power factor. The researchers should develop "plug and play" capacitors (and/or dial settable) for various climate zones to allow customization of HVAC motor/compressors by simple change out of capacitor by technicians, installers, or homeowners.

The researches have not yet arranged for commercial partners. They are seeking utility help to determine the value of improving power factor of residential HVAC systems. The researchers should investigate the potential benefits of improving power factors for other motor loads.

2.18.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary public benefit of this technology to California ratepayers would be reduced environmental impacts of the California electricity supply and transmission system.

For a typical cooling season in Los Angeles and a typical three ton central HVAC residential unit, if compressor run capacitance is not adjusted, utilities would generate and transmit 10,307 kVA hours of apparent power to meet 6,494 kW hours of real power. When run capacitance is adjusted, utilities would need to generate and transmit only 8,646.08 kVA hours of apparent power to meet 6,570 kW hours of real power demand for the same cooling load. The 16 percent saving on apparent power due to run capacitance adjustment should result in about 16 percent reduction in CO_2 emissions from power generation, assuming no change in generation mix, for residential HVAC end use application.

2.18.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.18.8.1 Marketing/Connection to the Market

The researchers should consider working with utilities and regulators on rate designs that specifically account for power factors in residential markets.

2.18.8.2 Engineering/Technical

The researchers validated the concept in hardware for a single residential application. They should undertake field testing across a range of geographic regions in California and in various HVAC equipment models prior to wide spread implementation. The researchers should develop "plug and play" capacitors for various climate zones to allow customization of HVAC motor/compressors by simple change-out of capacitor by technicians, installers, or homeowners.

2.18.8.3 Legal/Contractual

The researchers identified some patentable measurement devices, but at project's end had not applied for patents of those devices nor of the concepts in this research.

2.18.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

There are no known environmental or safety risks associated with the concept subject of this research. The researchers should develop quality plans that include specific design guidelines for matching motor capacitance to HVAC loads for a wider range of HVAC equipment.

2.18.8.5 Production Readiness/Commercialization

The subject of this research is ready for production in the sense that it is a design modification that should easily be incorporated into existing manufacturing processes.

2.19 Low Cost Laser Process for Fabricating Multi-Junction Solar Cells

Awardee: Nanotron, Inc.

Principal Investigators: Nathan Hiller

2.19.1 Abstract

The purpose of this project was to prove feasibility of a new technology to fabricate multi-junction solar cells. The researchers named the process Photo Thermal Electronic Nano-structuring or PTEN. The efficient conversion of sunlight into electricity by solar cells is challenging because the solar spectrum is composed of a wide range of frequencies. Single junction solar cells are moderately priced but their band gap must be chosen to be low to absorb low energy photons from the low frequency part of the spectrum. Consequently a large part of the energy of high energy photons is wasted as heat. Stacked multi-junction solar cells, composed of many thin film layers comprising multiple junctions, are more efficient because the different band gap energies more effectively use the solar spectrum. The additional complexity, however, comes with higher cost which has restricted their application to space craft and tracking solar concentrator systems. The purpose of this research project was to determine the feasibility of an inexpensive one step manufacturing process for multi-junction cells which uses polarized laser light to simultaneously fabricate multiple p-n junctions in

doped wafers. The researchers' immediate objective was to prove that spatial modulation of dopants in a semiconductor could be achieved using this process and that the modulated doping would efficiently couple to a wide range of frequencies in the solar spectrum. The researchers did not demonstrate feasibility of the technique in this project.

Keywords: Photovoltaic, multi-junction, modulated dopant laser processing, solar cell, fabrication

2.19.2 Introduction

This project had the twin goals of increasing the electrical conversion efficiency of photovoltaic (PV) cells and of lowering cell cost per unit electrical energy output. A limitation of the industry dominant single junction cell architecture is that a single band gap cannot be chosen to match the entire solar spectrum. The band gap energy has to be chosen so that photons from most of the solar spectrum have enough energy to excite electrons across the band gap. However the excess energy above the band gap of the photons from the higher energy part of the solar spectrum is wasted. Nevertheless, research on silicon based single junction cells has continued to advance up to 24.7 percent efficiency under standard global AM1.5 spectrum.[29] To circumvent the problem of matching one band gap to the solar spectrum, series connected monolithic multi-junction cells have been developed, which are composed of thin film layers of stacked junctions with the higher band gap junction on the top facing the sun. The top junction efficiently absorbs the higher energy part of the solar spectrum, allowing the low energy photons to pass through to a lower band gap junction that efficiently absorbs them. The multi-junction approach has produced cell efficiency as high as 32.0 percent using three junction cells under the AM1.5 spectrum.[1] Multi-junction cells when coupled with solar concentrators have even higher efficiencies up to 40.7 percent.[30] There is, however, some divergence of view on how to compare efficiency at one sun intensity and up to several hundred in concentrator tests.[31] Despite the fact that over two million multi-junctions have been fabricated[32] for the space program and solar concentrators, the series of expensive steps in fabricating the junctions makes them prohibitively expensive for most single sun commercial applications.

If the two goals of increasing cell efficiency and lowering cell cost are achieved, the California ratepayers could receive significant benefits. Solar energy systems in 2008 still cost approximately seven to ten dollars per watt. The high initial cost is a barrier to greater adoption of solar renewable energy.

The advancement of science proposed in this project was the innovative fabrication process. The researchers proposed a laser process to fabricate multi-junction stacks in a solar cell using relatively inexpensive equipment. The researchers called this process Photo Thermal Electronic Nano-structuring (PTEN). This process is outlined in Figure 19 below. A doped wafer is placed

29 http://www3.interscience.wiley.com/cgi-bin/fulltext/114281801/PDFSTART

30 http://www.energy.gov/news/4503.htm

31 http://www.amonix.com/Technical_Papers/2005/Silicon%20or%20MJ%20San%20Diego%202005.pdf

32 http://www.boeing.com/news/releases/2006/q4/061024c_nr.html

in the standing wave field set up by two linearly polarized counter propagating laser beams of the same wavelength and heated. At elevated temperatures the dopant atoms are free to diffuse. The dopant atoms at the antinodes of the standing wave are ionized by absorbing photons and the ionized dopant atoms diffuse to the antinodes by a process described by the researchers as "charge state dependent diffusion." These ionized dopant atoms are then analyzed in a model calculation. At the nodes of the standing wave, where there is no field, the ionized dopants can revert to a charge zero state. Once steady state is reached, the wafer is cooled to a temperature where the diffusion rate is negligible and the impurity distribution is locked in place. As an alternative the initial doped wafer can be compensated with both n-type and p-type atoms present. In this case one type of dopant diffuses to the node and the other is preferentially found at the antinodes yielding a stack of p–n junctions as shown in Figure 20. The presence of alternating layers of dopants modulates the host's band structure. Of particular note is the presence of spatially indirect transitions, which allow a sub band gap photon to excite an electron across the smaller effective band gap. Finally, to achieve a stack of graded band gap junctions, the researchers proposed (not shown) starting with a wafer having a monotonically decreasing dopant concentration from left to right surface or alternatively setting up a standing wave of monotonically varying intensity through the wafer.

Figure 19: PTEN Stack Fabrication

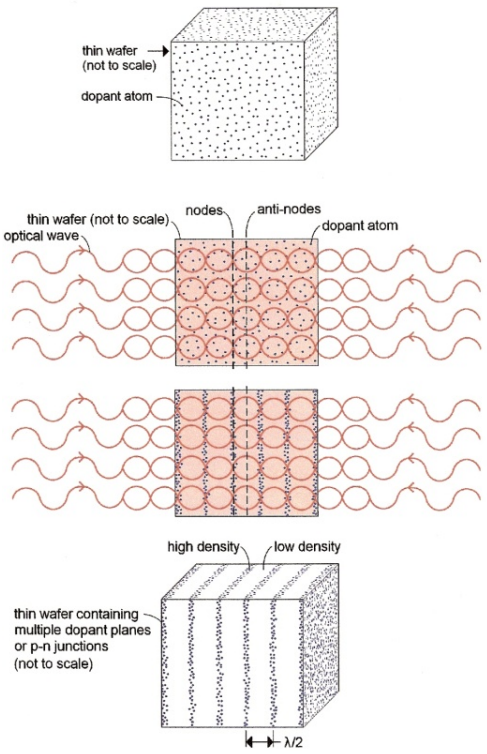
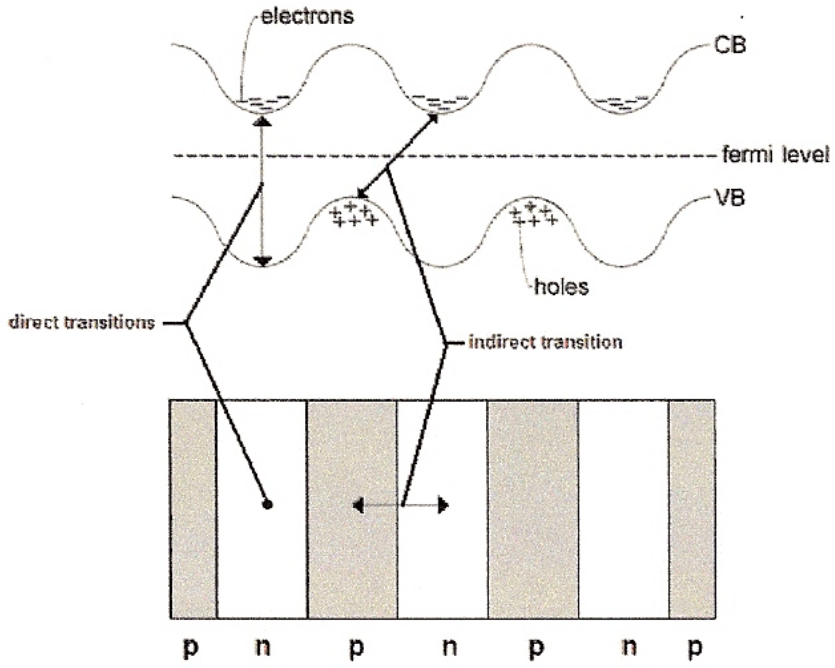


Figure 20: Modulated Stack Band Structure



2.19.3 Objectives

The goal of this project was to determine the feasibility of using a laser to fabricate multiple p-n junctions in a wafer for use as an affordable multi-junction solar cell. The researchers established the following project objectives:

1. Confirm through microscope visual inspection that laser standing wave pattern exists on film.
2. Confirm that dopant concentration variations in purchased silicon (Si) and cadmium sulfide (CdS) wafers are less than 5 percent in any given plane of the wafers.
3. Confirm that dopant peak to trough modulation is at least 10 percent from quasi-layer to quasi-layer.
4. Overlay transmittance curves of PTEN processed wafers and the control wafers and confirm that the PTEN processed wafers have a significant region of depressed transmittance (absorption) below the Si and CdS band gaps.

2.19.4 Outcomes

1. The researchers employed a slight wedge shaped CdS wafer, which was coated with a metal film on one side that was illuminated by a laser beam normal to the uncoated surface. Wedge angle was unspecified. By interference the incoming and reflected beams created a standing wave pattern in the wafer. Instead of using photographic film,the

standing waves were imaged on an optical filter by an interferometric technique. The researchers did not present quantitative results (wedge angle, band spacing, standing wave length).

2. The researchers employed secondary ion mass spectroscopy (SIMS) measurements on (unprocessed) CdS wafers doped with copper (Cu). Silicon was dropped for band gap considerations. Measured Cu concentrations as a function of depth were constant to within 0.1μ of the surface. The researchers did not present transverse dopant concentration data.

3. The researchers observed no dopant modulation in PTEN processed wafers. SIMS analysis revealed no deviation from uniform concentration down to a depth of 20 ◎ in laser processed CdS wafers doped with Cu and processed via PTEN.

4. The researchers made no attempt to achieve this objective because of the negative result of Objective 3.

In view of the negative result in Outcome 3, the investigators conducted several new research tasks leading to a new outcome:

The researchers coated a wafer of "semiconductor X" with material "Y". The coated surface was illuminated with a laser beam diffracted by a razor edge. Presumably this diffraction would produce a pattern of straight maxima and minima on the laser surface. The wafer was not heated. Scanning electron micrographs taken at low voltage and low magnification displayed diffuse circular ring features on the wafer surface.

2.19.5 Conclusions

1. Indirect evidence suggested the researchers met this objective. However no quantitative measurement data were presented in the final report.

2. As intended, the dopant concentration in an unprocessed wafer was constant as a function of depth. Therefore this objective was met.

3. SIMS analysis on laser processed wafers showed that the dopant concentration remained uniform with no indication of a dopant concentration modulation. Therefore this important objective was not met. The researchers inferred from this result that their laser was of too low power to create the required high intensity standing wave.

4. This objective was not attempted due the negative results in Objective 3.

5. The researchers speculated that impurity atoms were driven into the circular rings near the surface of the wafer and that these rings appear to be dopant modulation. The researchers did not speculate on why there would be circular ring pattern instead of a straight pattern. They presented no other support for this hypothesis.

2.19.6 Recommendations

The Program Administrator recommends experiments to confirm a standing wave of the expected wave length exists in a crystal of measured wedge angle. The experiments should use quantitative measurement of interference bands on the crystal. Before additional research is

begun the researchers should assemble a committee of experts in this field to review the hypothesis and to suggest alternate processing methods.

2.19.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California electricity supply, transmission, and distribution system. Deployment of an efficient PV technology can improve air quality by the displacement of carbon based fuel combustion in electricity generation. One analysis concluded that in 1999 California's electricity sector, including imports, released 106 million metric tons of carbon dioxide (CO_2).[33] If photovoltaics displaced just 10 percent of carbon based fuel generation, the release of over 10 million metric tons of CO_2 into the atmosphere could be eliminated.

2.19.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.19.8.1 Marketing/Connection to the Market

No additional information on market connection was available at the time of this report.

2.19.8.2 Engineering/Technical

No addition information on engineering/technical work was available at the time of this report.

2.19.8.3 Legal/Contractual

The researchers reported that they had applied for three patents.

2.19.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

There is no evidence that these issues had been addressed

2.19.8.5 Production Readiness/Commercialization

Since technical feasibility was not demonstrated, the technology in this project is not ready for commercialization.

33 http://www-library.lbl.gov/docs/LBNL/499/45/PDF/LBNL-49945.pdf

2.20 Nano-particle Based Catalysts for Solar Hydrogen Generation

Awardee: University of California, Davis

Principal Investigators: Frank E. Osterloh

2.20.1 Abstract

The goal of this project was to prove feasibility of a new method to split water into gaseous hydrogen and oxygen using nano-structured photo-catalysts and sunlight. The proposed approach was to synthesize a type of linear structured antenna catalyst employing $Ca_2Nb_3O_{10}$-Pt-TiO_2. Early tests showed that the catalytic activity was limited by lack of oxygen evolution from water and an inability to absorb light in the visible region of the spectrum. To address these problems, the researchers redirected their efforts to three new materials: $HCa_2Nb_3O_{10}$ – IrO_2 nano-composite, $K_4Nb_6O_{17}$ nano-sheets and nano-scrolls with and without Pt, and CdSe nano-ribbons. The catalysts were built from exfoliated semiconducting nano-sheets or nano-scrolls derived from the layered perovskites $KCa_2Nb_3O_{10}$ and $K_4Nb_6O_{17}$ or from cadmium selenide (CdSe) nano-ribbons. Using linker molecules, IrO_2 or platinum particles were attached to the $HCa_2Nb_3O_{10}$ nano-sheets. The researchers functionalized nano-sheets/scrolls derived from $K_4Nb_6O_{17}$ with platinum particles by photochemical deposition of K_2PtCl_6. All catalysts were fully characterized with transmission electron microscopy and ultraviolet and infrared spectroscopy. Under ultraviolet irradiation, all niobate catalysts evolved hydrogen from water with quantum efficiencies of up to 4.69 percent. No oxygen was evolved, which was attributed to the adsorption of oxygen to the catalyst surface, forming super oxide or peroxide. For Pt-[$HCa_2Nb_3O_{10}$] the adsorption process shut down hydrogen evolution after 12 hours of constant irradiation, but the activity could be partially restored by purging the catalyst dispersion with argon gas. Significantly, for CdSe nano-ribbons catalytic hydrogen evolved at 13 percent efficiency under visible light and at 10 percent efficiency under ultraviolet light. The activity of CdSe is remarkable because bulk CdSe is known to be not active for the reaction. The researchers speculated that the activity of CdSe nano-ribbons was a result of quantum confinement effects

Keywords: Renewable energy, hydrogen, water splitting, photochemical catalyst, nano-structure, niobate, cadmium selenide, quantum confinement

2.20.2 Introduction

In 2008 qualified renewable energy sources (biomass, geothermal, hydroelectric, solar, wind) comprised only 12 percent of California's electricity production, while carbon based fuels comprised up to 62 percent of the total.[34] The burning of carbon based fuels can degrade air quality and can introduce uncertainties in the future cost of electricity due to market price fluctuations. These attributes of carbon based fuels make renewable sources attractive for the future electricity supply. The solar component of the renewable mix is particularly attractive

34 http://www.energyalmanac.ca.gov/overview/energy_sources.html

because the resource is well matched to California's electricity demand. Market penetration has been hampered by high cost and the lack of a means to store solar energy for use at times of low or limited sunlight.

Photochemical splitting of water to produce gaseous hydrogen is attractive as a means to store the energy of solar photons in the form of chemical potential energy of hydrogen molecules.[35] Photolysis is a proven method of producing free hydrogen from water. In this method a semiconductor catalyst in a water bath, either alone or with a metal contact, absorbs a photon to create an excited free electron and hole pair that can split the water at the catalyst surface. To split a molecule of water requires a minimum energy of 1.23 electron volts (eV) per molecule and thus the band gap of the semiconductor must be greater that 1.23 V for the electron hole pair to be able to supply the necessary energy. In practice only much larger band gap materials, e.g., ZnS with a band gap of 3.6 eV,[36] are efficient in splitting water. Because of their large band gap they require ultraviolet photons, which are a very small part of the solar spectrum. Thus the large band gap materials are not practical. A smaller band gap material, e.g., CdSe with a band gap of 1.74 eV[3], would use much more of the solar spectrum. However all have been found to be very inefficient in splitting water and are sensitive to decomposition in water. The inefficiency has been attributed to short free carrier recombination time so that the electron hole pairs recombine before they diffuse to the catalyst surface. Prior to this project no material capable of catalyzing the water splitting reaction with visible light exhibited quantum efficiency (hydrogen produced/ photons absorbed) greater than 10 percent.[37] Other researchers have established a chemical conversion process efficiency of 10 percent as a near term technical benchmark for a practical water splitting catalyst.[38]

If the efficiency goal and the cost goal could be met, hydrogen generation using solar energy could provide the basis for greatly enlarged use of solar energy in California. The electricity ratepayer would benefit from electricity generated by hydrogen fueled generators in large utility scale plants with low emissions. Hydrogen/air combustion in gas turbines can produce high levels of oxides of nitrogen if not properly controlled. Electricity generation by either grid tied or stand alone hydrogen powered fuel cells would be of benefit in intermediate sized application. In transportation, hydrogen fueled internal combustion vehicles offer some advantages over today's gasoline vehicles. The main advantage would accrue if the fuel could be generated at the house level. Exhaust emissions could be a problem with hydrogen fueled internal combustion engines. Hydrogen fuel cell powered electric vehicles would be a more attractive option for transportation.

The advancement of science or technology proposed in this project for hydrogen production was a novel nano-particle composite catalyst that separated the functions of light absorption, water reduction, and water oxidation. This structure was intended to increase efficiency by

35 http://www1.eere.energy.gov/hydrogenandfuelcells/

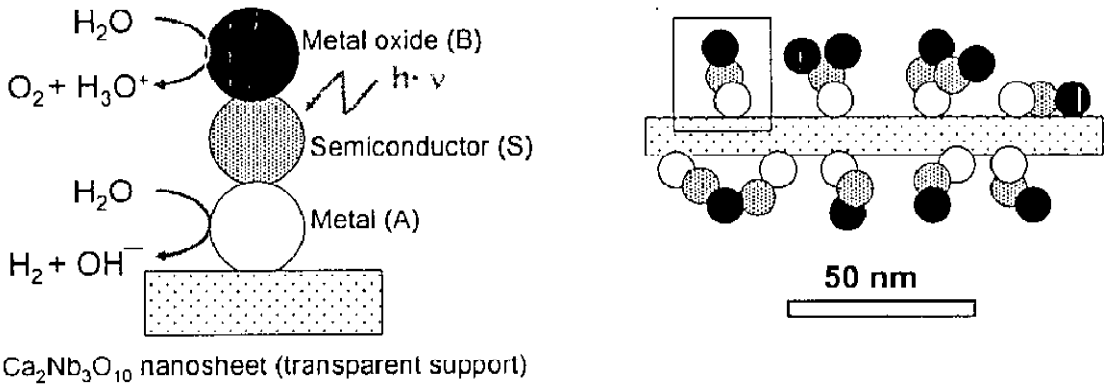
36 http://hyperphysics.phy-astr.gsu.edu/Hbase/tables/semgap.html

37 F.E. Osterloh, Chem. Mater **20**, 35 (2008)

38 http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/production.pdf

spatially separating the photo produced electron hole pair and thus greatly decreasing the recombination rate. A schematic of the cluster structure is shown in Figure 21. The metal-semiconductor-metal oxide or A-S-B structure was designed to separate the electron hole pair when they were created in the semiconductor. Because the chemical potentials of A and S are different, electric fields are set up at the A-S interface which makes it energetically favorable for the electron to go to A. A different electric field at S-B causes the hole to go to B. The spatial separation of the electron hole pair decreases the recombination rate. At A the electron can reduce water to hydrogen gas. At B the hole can oxidize water to oxygen. In this case the hydrogen and oxygen gases bubble out of solution where they are collected. To create the composite nano-structures, researchers deposited the constituent materials out of solution onto transparent substrates of calcium niobate in the form of nano-scrolls or nano-sheets. The researchers expected a wide variety of aggregates formed, as indicated in the right image of Figure 21. The researchers hypothesized that the high degree of redundancy would prevent the efficiency from being significantly limited.

Figure 21: Schematic Structure of the Nano-Particle Cluster Catalyst



The diagram above shows transparent support and individual particles as sites for light absorption, water oxidation, and reduction. The right image is a schematic view of a larger section of the nano-sheet showing several copies of the A-S-B motif and a scale bar.

2.20.3 Objectives

The goal of this project was to determine the feasibility of using multi component nano-particle based structures as catalysts for the visible light driven splitting of water into hydrogen and oxygen. The researchers established the following project objectives:

1. Demonstrate oxygen and hydrogen separation and detection at sub micro-molar concentrations.
2. Demonstrate catalyzed hydrogen evolution from water at potentials near zero volts (normal hydrogen electrode, NHE).
3. Demonstrate hydrogen evolution at greater than 1 percent efficiency using $Ca_2Nb_3O_{10}$-Pt.

4. Prove that the $Ca_2Nb_3O_{10}$-Pt-TiO_2 concept can achieve catalyst target structure.
5. Prove that hydrogen evolution takes place at potential close to zero volts (NHE). Determine effect of catalyst illumination with visible/ultraviolet light on hydrogen evolution.
6. Demonstrate hydrogen evolution at greater than 1 percent efficiency and demonstrate increased hydrogen evolution compared to $Ca_2Nb_3O_{10}$-Pt.
7. Switch research to $Ca_2Nb_3O_{10}$-Pt-TiO_2 –Fe_2O_3 or modify synthetic approach if performance of $Ca_2Nb_3O_{10}$-Pt-TiO_2 catalyst is insufficient.
8. Demonstrate that synthetic approach works with $Ca_2Nb_3O_{10}$-Pt-TiO_2 –Fe_2O_3.
9. Demonstrate that hydrogen and oxygen evolution takes place at potentials near zero volts and 1.4 volts, respectively.
10. Demonstrate hydrogen evolution at greater than 1 percent efficiency.
11. Synthesize $Ca_2Nb_3O_{10}$-Pt-CdS and demonstrate that synthetic approach works.
12. Demonstrate that hydrogen evolution takes place at potentials near zero volts. Also show the effect of visible light irradiation on gas evolution rate.
13. Acquire photo-catalytic data on $Ca_2Nb_3O_{10}$-Pt-CdS. Demonstrate hydrogen evolution at greater than 1 percent efficiency with visible light irradiation.
14. Conduct photo bleaching studies on $Ca_2Nb_3O_{10}$-Pt-TiO_2-Fe_2O_3. Demonstrate reduced lifetime of TiO_2 excited state compared to TiO_2 alone. Obtain numerical values for charge transfer kinetics from TiO_2 to Pt and Fe_2O_3.

2.20.4 Outcomes

1. The gas chromatograph demonstrated oxygen and hydrogen detection down to the parts per million level.
2. The researchers collected electrochemical data on $HCa_2Nb_3O_{10}$ (layered perovskite) and on $HCa_2Nb_3O_{10}$-Pt. Both catalysts oxidize and reduce water. For $HCa_2Nb_3O_{10}$ water oxidation takes place at +1.24 volts and reduction at -1.62 volts (using a normal hydrogen electrode, NHE, as reference). For $HCa_2Nb_3O_{10}$-Pt the researchers measured oxidation at +1.22 volt and reduction at -1.36 volt.
3. Under ultraviolet irradiation, $HCa_2Nb_3O_{10}$ produced H_2 at 0.17 percent efficiency by photo-catalysis and $HCa_2Nb_3O_{10}$-Pt at 4.69 percent efficiency. After 8 hours the hydrogen rate dropped for $HCa_2Nb_3O_{10}$-Pt and became zero after 12 hours. Hydrogen activity was restored by purging the catalyst with argon gas.
4. The researchers did not synthesize the structure $Ca_2Nb_3O_{10}$-Pt-TiO_2. Tests showed that the catalytic activity was limited by lack of oxygen evolution from water and an inability of TiO_2 to absorb light in the visible region of the spectrum. To address these problems, the team focused on the following materials: $HCa_2Nb_3O_{10}$ – IrO_2 nano-composite, $K_4Nb_6O_{17}$ nano-sheets and nano-scrolls with and without platinum, and CdSe nano-

ribbons. The team synthesized catalysts and characterized them using electron microscopy, visible spectroscopy, photochemical, and electrochemical measurements.

5. $Ca_2Nb_3O_{10}$-Pt-TiO_2 was not synthesized. Electrochemical data on $HCa_2Nb_3O_{10}$ – IrO_2 showed that oxygen evolution could be achieved at +0.61 volt (NHE).
6. Tests on $HCa_2Nb_3O_{10}$–IrO_2 demonstrated hydrogen evolution at 1.54 percent efficiency. However IrO_2 was found to decompose to metallic iridium under photo-catalytic conditions.
7. Since the performance of $Ca_2Nb_3O_{10}$-Pt-TiO_2 catalyst was insufficient, the synthetic approach was modified to focus the research on $K_4Nb_6O_{17}$ nano-sheets and nano-scrolls and on CdSe nano-ribbons.
8. The researchers synthesized $K_4Nb_6O_{17}$ nano-sheets and nano-scrolls both with and without Pt and CdSe nano-ribbons.
9. Electrochemical measurements on $K_4Nb_6O_{17}$ nano-sheets and scrolls showed that the addition of platinum nano-particles to the catalyst made water reduction easier, e.g., the water reduction potential shifted from -1.62 volts to -1.42 volts.
10. All systems derived from $K_4Nb_6O_{17}$ evolved hydrogen from water under ultraviolet light. Although time resolved hydrogen evolution studies showed saturation, the efficiencies were higher than for $HCa_2Nb_3O_{10}$, especially after adding platinum as co-catalyst.
11. Since none of the metal oxide catalysts had absorption in the visible spectrum, CdSe nano-ribbons were synthesized for further study.
12. Photo-catalytic tests showed that mild reducing agents such as Na_2SO3 or Na_2S were required to prevent the catalysts from decomposing under illumination.
13. Significantly, under both ultraviolet and visible light CdSe nano-ribbons evolved hydrogen from 1.0 molar aqueous solution of Na_2S and Na_2SO_3 with efficiencies of 10 to 13 percent.
14. Photo bleaching studies of $HCa_2Nb_3O_{10}$ nano-sheets revealed that the lifetimes of the photo generated electrons and holes were 0.28 to 0.52 nano-seconds, respectively, depending on excitation energy and nano-sheet size.

2.20.5 Conclusions

1. The researchers met this objective.
2. Electrochemical data were acquired on $HCa_2Nb_3O_{10}$ and on $HCa_2Nb_3O_{10}$-Pt. Both catalysts oxidized and reduced water, meeting this objective.
3. Under ultraviolet irradiation, $HCa_2Nb_3O_{10}$ produced H_2 at 0.17 percent efficiency by photo-catalysis and $HCa_2Nb_3O_{10}$-Pt at 4.69 percent. This objective was met.

4. The researchers did not synthesize the structure $Ca_2Nb_3O_{10}$-Pt-TiO_2. Tests showed that the catalytic activity was limited by lack of O_2 evolution from water and, in addition, an inability to absorb light in the visible region of the spectrum as expected.

5. Electrochemical measurements on alternative material $HCa_2Nb_3O_{10}$ – IrO_2 showed that O_2 evolution could be achieved at +0.61 V (NHE).

6. Tests on alternative material $HCa_2Nb_3O_{10}$–IrO_2 demonstrated hydrogen evolution at greater than 1 percent efficiency. The efficiency was measured at 1.54 percent.

7. The researchers modified the synthetic approach to focus on $K_4Nb_6O_{17}$ nano-sheets and nano-scrolls and on CdSe.

8. This modified objective was met.

9. Electrochemical measurements showed that the addition of platinum nano-particles to $K_4Nb_6O_{17}$ nano-sheets and scrolls made water reduction easier. The modified objective was met.

10. All systems derived from $K_4Nb_6O_{17}$ evolved H_2 from water under UV light. Although time resolved hydrogen evolution studies showed saturation, the efficiencies were higher than for $HCa_2Nb_3O_{10}$, especially after adding Pt as co-catalyst. The modified objective was met in part.

11. Since none of the metal oxide catalysts above has significant absorption in the visible spectrum, the team successfully explored the catalytic properties of CdSe nano-ribbons.

12. The researchers concluded that mild reducing agents such as Na_2SO3 or Na_2S are required to prevent the CdSe catalysts from decomposing under illumination.

13. Under illumination CdSe nano-ribbons evolved hydrogen from 1.0 M aqueous solution of Na_2S and Na_2SO_3 with 10 percent efficiency in the ultraviolet and 13 percent efficiency in the visible. This modified objective was met.

14. Although the researchers did not carry out photo bleaching studies on nano-structures of $Ca_2Nb_3O_{10}$-Pt-TiO_2-Fe_2O_3 as originally planned, such studies on $HCa_2Nb_3O_{10}$ nano-sheets were shown to be a promising first step in the better understanding of photo-catalysts. The measured lifetimes of the photo generated electrons and holes were short (0.28 to 0.52 ns), but could possibly be extended by adding platinum as a co-catalyst.

The researchers demonstrated for the first time that nano-sheet semiconductors derived from CdSe, $K_4Nb_6O_{17}$, and $KCa_2Nb_3O_{10}$ will catalyze hydrogen evolution from water during illumination. The metal oxides are only sensitive under ultraviolet light, and the nano-structured forms of the metal oxides are not more efficient than the bulk form. When the researchers tested CdSe nano-ribbons, the ribbons evolved hydrogen both in ultraviolet, and most importantly, in the visible. In contrast, bulk CdSe was not active for this reaction. The researchers concluded that the catalytic activity of CdSe nano-ribbons was due to quantum confinement effects as a result of nano-size effects. For CdSe, the researchers speculated that the enhanced activity was brought about by the nano-size effects modifying the energy band structure of the materials. The researchers reported that CdSe nano-ribbons dissolved under

photo-catalytic conditions in pure water without the presence of mild reducing agents. The researchers speculated that these materials can potentially be operated in pure water after modification with IrO_2 co-catalysts.

In principle, nano-structures can be exploited to convert other inactive materials into active photo-catalysts. However, despite the nano-size and greater surface area, the catalytic activities of the niobate nano-sheets were not always superior to bulk $K_4Nb_6O_{17}$ and $KCa_2Nb_3O_{10}$. Water oxidation turned out to be a problem because of adsorption of the oxygen onto the catalyst surface, presumably as a peroxide. Although the adsorption process disabled the most active catalysts over the course of 12 hours, catalytic activity can be restored by purging with an inert gas.

2.20.6 Recommendations

Nano-sheet based niobium oxides and cadmium selenides were shown to be catalysts for photochemical water splitting, both with ultraviolet light and in the case of CdSe with visible light. Further research would be better spent on materials with band gaps in the visible light for a better match to the solar spectrum and with the addition of co-catalysts for water oxidation. The Program Administrator recommends that future research address the reasons for increased photo-catalytic activity. Is it due to quantum confinement modifying energy bands structure, or is it due to dangling surface and edge bonds as active sites?

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.20.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California electricity supply, transmission, and distribution system. If the technical goals for efficiency and cost can be met, hydrogen gas derived from solar energy has the potential to solve several major challenges facing California today. These challenges include dependence on petroleum imports, poor air quality, and greenhouse gas emissions. The electricity ratepayer

would benefit from electricity generated by hydrogen fueled utility scale generations plants. The electricity would be generated with a renewable fuel and produce low air emissions. Similarly, electricity generation by either grid tied or stand alone hydrogen powered fuel cells would be of benefit in intermediate sized applications. In transportation, hydrogen fueled internal combustion vehicles offer many advantages over today's gasoline vehicles. Hydrogen fuel cell powered vehicles could be an attractive alternative to gasoline fueled hybrid vehicles if fuel cell costs decline.

2.20.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.20.8.1 Marketing/Connection to the Market

The researchers published two papers on this work in scientific journals. Four other manuscripts were planned. The researchers reported that four talks on the work were given at meetings in 2008.

2.20.8.2 Engineering/Technical

No new engineering or technical information was available at the time of this report.

2.20.8.3 Legal/Contractual

The researchers applied for multi-year grants to the National Science Foundation (NSF) and the Department of Energy. NSF funded a three year project in 2008. The researchers had not applied for patents at the writing of this report.

2.20.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

Since cadmium and selenium are toxic materials, the researchers must address the use of these materials from a safety point of view. Use of hydrogen as a fuel must be addressed from a safety point of view. Hydrogen combustion in turbines or reciprocating engines must be closely monitored to ensure low air emissions. These issues must be addressed once the technology has been proven.

2.20.8.5 Production Readiness/Commercialization

The researchers talked to a company about large scale production of catalysts.

2.21 Use of Plasma Actuators to Increase Wind Energy Extraction

Awardee: Clarkson University

Principal Investigators: Kenneth Visser

2.21.1 Abstract

The University of Notre Dame and Clarkson University jointly pursued this project to prove the feasibility of plasma actuators to increase the energy extraction of small wind turbines. Researchers conducted wind tunnel experiments on blade sections from a Bergey XL.1 turbine at the University of Notre Dame.

The pressure, force, and flow visualization results concluded the plasmas actuators did not improve the lift to drag ratio on the tested wing as expected, but instead increased the maximum value of the lift coefficient. This indicated the efficiency of the wing was not improved; however, the condition under which the wing would stall was delayed.

The researchers did not complete full scale tests at the Clarkson University Wind Turbine Test Site due to complications that arose while attempting to apply the plasma actuator technology to blades suitable for mounting on the full scale turbine.

Although the grant period ended, the grantee's final report stated that work was continuing on the project with the goal of a working prototype for data collection in early 2009. The grantee also stated progress had been made in development of a viable actuator and Clarkson University would continue to support this effort internally until the project demonstrated whether this technology is effective on a full scale turbine. Although the grantee's final report stated they would provide additional data, they submitted no further project information.

Keywords: Plasma actuator, wind turbine, wind tunnel, lift, drag, electricity, generation

2.21.2 Introduction

Nearly 1.5 percent of California's 2004 electricity needs, totaling 4,258 million kilowatt hours of generation, were provided by wind energy generated in California.[39] As the state moves toward the goal of deriving 33 percent of its electricity from renewable sources by 2020, the percentage of electricity produced by wind energy in California will also rise. Technologies that increase efficiency of wind production for both new and existing facilities can help meet these renewable goals while also decreasing the cost of wind energy to the state's ratepayers.

Wind turbines typically operate in environments characterized by vertical wind shears, gusts, and changing wind directions. While modern wind turbine blades can be designed to achieve nearly optimum performance in steady winds, their performance is degraded when the wind is non-uniform or unsteady. These off design conditions reduce aerodynamic performance and lower energy extraction. In addition, these conditions give rise to unsteady blade loadings, noise generation, and structural vibration that result in blade fatigue. Turbine blades and support structures are typically over designed to minimize the risk of these problems to the facility's structural integrity. The additional costs that result could be reduced should these off design conditions be mitigated.

39 http://www.energy.ca.gov/wind/overview.html

One potential method for improving wind production is through the use of plasma actuators. According to Sandia National Laboratories (Sandia),[40] the use of plasma actuators as a means of aerodynamic flow control is new with little published on the subject before 2000. Sandia cites simple research begun in the 1990s using a very basic plasma actuator as the catalyst for additional work conducted by researchers in the field of aerodynamics. Sandia estimated that more that 30 groups were working in the field and over 150 papers had been published when its report was produced in August 2008. In April 2009 the University of California Los Angeles announced plans to develop a new turbine lab in downtown Los Angeles.[41]

As defined in the Sandia report,[42] surface non-thermal plasma actuators operate by creating an electric field between two electrodes, an anode (+) and a cathode (-). By applying a large voltage difference between the electrodes, an electric field is formed and induces an electric wind, or ionic wind, close to the surface. The electric wind is formed by collisions between drifting ions and the neutral particles in the electrode gap region. The induced wind acts as a body force and drives the nearby fluid, creating a zero net mass flux (ZNMF) jet, modifying the boundary layer airflow profile and postponing separation. The behavior of the actuators is dependent on geometrical parameters (electrode shape and size, gap distances, etc), electrical parameters (voltage, waveform, and frequency if AC, etc), and ambient air properties.

The researchers proposed to prove the feasibility of using active flow control technology to improve wind turbine efficiency. Wind turbine efficiency is degraded due to non-uniform wind conditions such as gusting and directional changes. Unsteady and non-uniform wind conditions are the norm rather than the exception for an operational wind turbine, and thus the likelihood of stall occurring on portions of the turbine blades is an operational reality. In addition, blades that are not twisted, such as on the Bergey XL.1, see a non-optimum angle of attack at every radial condition except one, further exacerbating this effect.

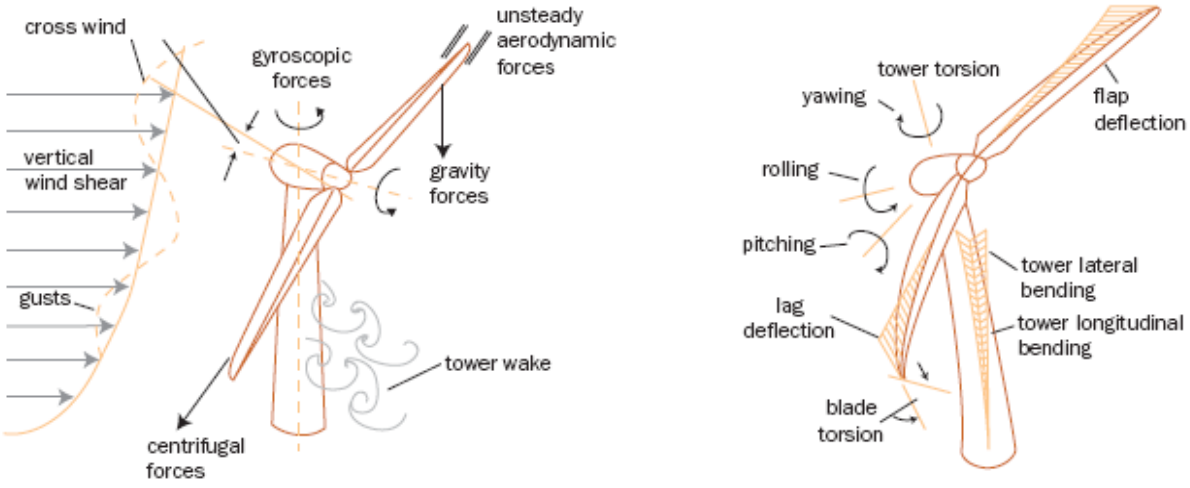
Figure 22 highlights the problems mentioned above. The figure on the left illustrates the flow issues and unsteady aerodynamics, while the figure on the right shows the structural issues.

40 Johnson, Scott J., C. P. van Dam, and Dale E. Berg. *Active Load Control Techniques for Wind Turbines.* Sandia National Laboratory. SAND2008-4809, August 2008, p. 85.

41 Anzelc, J. "UCLA to build turbine lab," *Daily Bruin*. April 29, 2008. http://www.dailybruin.com/articles/2009/4/29/ucla-build-turbine-lab/

42 Johnson, et al, p. 82.

Figure 22: Sketch of Wind Turbine Loads and Structural Modes



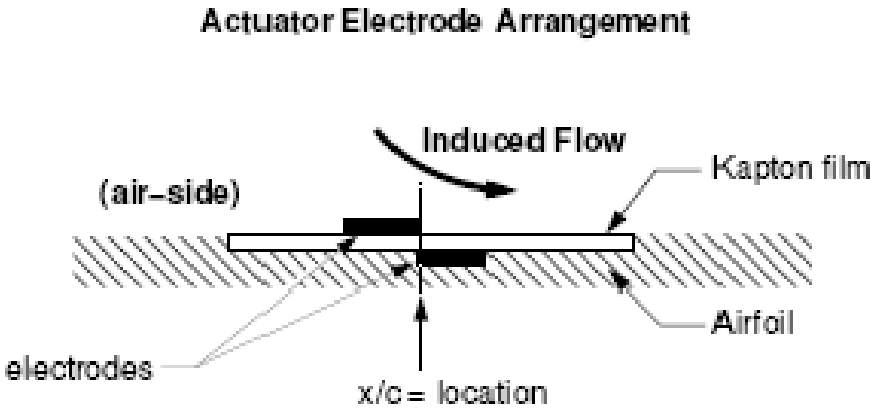
a) External forces acting on turbine

b) Vibration and deflection modes

Dr. Thomas C. Corke of the University of Notre Dame specializes in the application of single dielectric barrier discharge (SDBD) plasma actuators for controlling flow separation, lift enhancement, and drag reduction. His research is based on the initial demonstration of the concept performed by United Technologies and NASA.

The SDBD plasma actuator proposed for this grant consisted of two electrodes as shown in Figure 23. The thin electrodes are typically made of copper foil tape. One electrode is exposed to the air, while the other is encapsulated in a dielectric material. When the alternating current voltage reaches the proper amplitude, the flow over the encapsulated electrode begins to ionize. The ionized air and the electric field of the electrodes create a force that acts on the air flowing over the actuator. The flow can be tailored by the arrangement and orientation of the electrodes.

Figure 23: Plasma Actuator Concept



2.21.3 Objectives

The objective of this project was to prove the feasibility of increasing the power output of wind turbines by increasing their aerodynamic efficiency using plasma actuators as a means of active flow control technology. The researchers predicted increased generation of power at a given wind speed as well as extraction of more energy at lower speeds. They established the following project tasks and objectives:

1. Conduct a wind tunnel study at the University of Notre Dame. The use of the plasma actuator delays the stall of the wing for about seven degrees and improves the maximum lift coefficient by about 10 percent. Target a 50 percent improvement in stall margin, a 16 percent improvement in maximum sectional lift coefficient (Cl_{max}), and a 10 to 15 percent reduction in sectional drag coefficient (C_d) at high angles of attack.
2. Conduct a full scale study at Clarkson University. Demonstrate improvement of the coefficient of pressure (C_p) of approximately 10 percent above the baseline (no flow control) turbine based on a torque increase at the optimum blade angle at a given tip speed ratio. Evaluate the relative impact on gusting versus directional changes.
3. Conduct a cost benefit analysis. Determine the associated cost over the life cycle of the machine when compared to energy generation without plasma actuators. This includes accounting for the use of the energy required to drive the plasma flow control actuators (estimated at less than three watts for the entire rotor under operating conditions), the cost of actuator equipment, and the associated increase in energy harvested.

2.21.4 Outcomes

1. The targeted improvements for Objective 1 were a 50 percent improvement in stall margin, a16 percent improvement in Cl_{max}, and a 10 to 15 percent reduction in C_d at high angles of attack. The study found, however, that the actuator delayed the stall of the wing for another five to six degrees, not the expected roughly 40 percent improvement in margin. While the maximum lift coefficient increased by about 10 percent as expected, the researchers did not observe reduction in C_d.
2. There was no demonstration of an improvement of C_p of approximately 10 percent above the baseline (no flow control) turbine based on a torque increase at the optimum blade angle at a given tip speed ratio. The researchers stated they would continue this work in the post grant period.
3. The researchers did not report outcomes since Objective 2 was not completed.

2.21.5 Conclusions

At the close of the grant period only Objective 1 was complete. The primary issue associated with the very long delay in initiating Objective 2, according to the researchers, was the development of a circuit suitable for powering the plasma actuators on the full scale wind turbine. Additional conclusions were:

1. The plasma actuators did not improve the aerodynamic efficiency of the wing in the operating regime.
2. The use of the plasma actuator improved the maximum lift coefficient and could thus be used to delay stall or initiate start-up conditions earlier on the blade. This could be applied to the present constant chord geometry blade of the Bergey XL.1 and also to a more optimized blade shape.
3. Powering a full scale plasma actuator required additional time and development that was not anticipated in the original grant application.
4. Feasibility was not proven.
5. The researchers offered to provide an addendum to the final report to EISG Program Administrator upon completion of Objectives 2 and 3 of the grant. No addendum was received during 2009.

2.21.6 Recommendations

The status of this project makes it difficult to recommend further steps until the full scale studies of Objective 2 and the analysis anticipated in Objective 3 of this grant have been completed. It is unclear when the grantee anticipates completing this work.

Several additional issues should be addressed by the researchers:

1. The laboratory work performed in Objective 1 appears to be irrelevant to wind turbine blades since these blades must be tapered chordwise across their span and twisted around their longitudinal axis. The researchers chose to use flat airfoils of constant chordal length along their axis. While this is adequate for most compressors and fans in the internal aerodynamics of aircraft engines where the blades are only a small radial segment of a propeller, such an approximation is inappropriate for wind turbines. The researchers should provide further detail for why this method was chosen.
2. In Objective 1 the researchers did not discuss why they chose a chordwise position for the plasma actuator location. They should justify this decision since current literature indicates the plasma actuator should be at the leading edge of the airfoil for the best effect of flow attachment and stall suppression.[43]
3. While attempting to locate the separation bubble, the researchers suddenly shifted their attention to locating the actuator at the leading edge, without citing the relevant literature or giving any other justification. The researchers should provide this information in the addendum.
4. The electrode geometry shown in Figure 24 of this report has no horizontal gap between the upper and lower electrodes. A gap of 1-2 mm typically produces optimum results. The researchers should explain the gap(s) used during testing in the addendum.

43 Johnson, et al, p. 86.

5. The actuator geometry resulting from this project appears unsuitable for a propeller or wind turbine blade. The researchers should address whether the plasma actuator should be completely recessed into the substrate of the blade to prevent the formation of vortices and drag due to ordinary airflow disturbance.

2.21.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is from reduced environmental impacts of the California electricity supply system. Because the work is incomplete, it is impossible to quantify any direct benefits to California ratepayers as a result of this grant. Should plasma actuator research prove successful, it could have significant impact on wind turbine benefits.

2.21.8 Overall Technology Transition Assessment

As the basis for this assessment the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.21.8.1 Marketing/Connection to the Market

The researchers did not identify a clear transition to commercialization for this technology.

2.21.8.2 Engineering/Technical

The primary feasibility issue is the development of a viable circuit to actuate the device on the full scale rotor blade. This work was continuing at the end of this grant. The researchers anticipated that the extra costs would be absorbed by their universities.

2.21.8.3 Legal/Contractual

The EISG Program Administrator is not aware of any patents or contracts related to this project.

2.21.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

Because the technical work was not completed during the term of the grant, any work on these plans would have been premature.

2.21.8.5 Production Readiness/Commercialization

Plasma actuators for use as a device to increase wind energy extraction clearly require additional research and testing before commercialization.

2.22 Prototype Energy Cell

Awardee: Primus Power Corporation

Principal Investigators: Rick Winter

2.22.1 Abstract

The purpose of this project was to demonstrate the technical feasibility of an inexpensive, highly efficient, and reliable flow battery for substation backup power. As increasingly large amounts of intermittent power resources are connected to the electric grid, the need for energy storage and immediate response backup increases, especially at the substation level. This project validated the feasibility of a flow battery design for this purpose. The researchers met their goal of establishing feasibility. System integrity, manufacturability, and design safety were key components of the prototype evaluation. Actual prototype performance exceeded pre-established goals of at least 50mA/cm^2 at 1.645Vpc with a pressure drop of 0.19 bar (2.8psi) through the reactor stack. The researchers filed a patent application with 74 separate claims for primary metal halide electrochemistry for backup power applications.

Keywords: Flow battery, EnergyCell™, backup power, substation power, zinc chloride

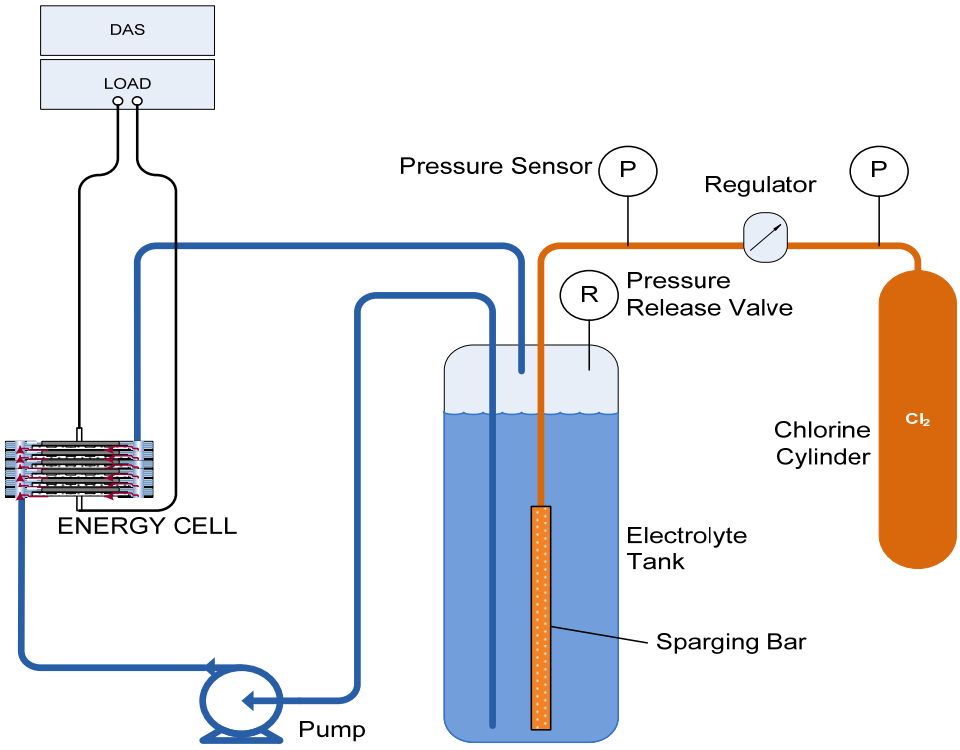
2.22.2 Introduction

California's renewable portfolio standard is being met increasingly with intermittent sources such as wind and solar. Intermittent sources, coupled with California's economic structure demanding higher quality power, have focused attention on the need for highly reliable backup power and energy storage options.

Currently energy storage options are expensive, inefficient, or focused on particular storage periods (e.g., sub-cycle, diurnal, seasonal). More importantly, today's substation backup power is typically met with lead acid batteries that pose safety and disposal risks and short storage backup capability of approximately four to six hours.

The researchers in this project designed and tested a new flow battery based on zinc chlorine chemistry that promises improved performance, longer storage time, and reduced maintenance costs. They have applied for patents on the system and have lined up potential host utilities for field demonstrations. Figure 24 illustrates the overall schematic of the system.

Figure 24: Prototype EnergyCellTM Test Setup



2.22.3 Objectives

The goal of this project was to demonstrate the feasibility of the EnergyCell™ flow battery for use as a substation sited energy backup and storage device. The researchers established the following objectives:

1. Complete one patent application.
2. Design and build a six cell prototype EnergyCell™.
3. Demonstrate a combined dynamic and static pressure drop of less than 0.3 bar (4.35psi) in the complete EnergyCell™ flow loop.
4. Demonstrate system integrity. The stack, reservoir, pump, and fittings were to be leak free over an extended operating period.
5. Demonstrate 25mA/cm^2 current density.
6. Verify $2,600 production cost for a 3.3kW/80kWh device.
7. Review the commercial practicality of the EnergyCell™ flow battery.

2.22.4 Outcomes

1. The researchers filed Patent Application # 288.1001.01 containing 74 claims on January 12, 2007.

2. The researchers fabricated a six cell EnergyCell™ based on a laser cut frame and gasket design.
3. The researchers measured a total pressure drop of 0.2 bar across the cell.
4. The researchers operated the system and found no leaks in the stack, reservoir, pump, or fittings.
5. The researchers measured 12V and 50mA/cm2 across the cell.
6. The researchers estimated a manufacturing cost of $1,920 for a 3.3kW/80kWh device.
7. The researchers confirmed the commercial practicality of the EnergyCell™ in the context of substation backup power.

2.22.5 Conclusions

1. The researchers confirmed the feasibility of the zinc chlorine flow battery for substation backup power application.
2. The researchers confirmed via literature and professional search that the EnergyCell™ design does not infringe on existing or expired patents.
3. The researchers confirmed that the zinc chloride flow battery system can be manufactured using inexpensive and readily available materials including PVC, polyethylene, metal plates, water, and a chloride based salt.
4. Production of these devices does not require any unique or specialized manufacturing techniques.
5. The combined pressure drop of less than 0.3 bar (4.35psi) in the complete flow loop demonstrated that the material selected as the cathode (commonly available zinc) is well suited to the application.
6. The prototype had the capability to supply a current of 25mA/cm2 at sustained voltage. This is the single most important factor in determining technical and commercial viability since 25mA/cm2 produces sufficient power to make a practical energy storage device.
7. The researchers confirmed the cost of production puts the capital cost of the product below the capital cost of equivalent lead acid systems.

2.22.6 Recommendations

The Program Administrator recommends that the researchers construct a larger field demonstration unit and test it side by side with a lead acid power system for direct comparison. They should design a volume production process that achieves the same or better cost reductions as achieved in the prototype that ensures product uniformity and reliability. Work should continue on reducing the design complexity and sourcing materials and components to bring the manufactured cost below $1,000 for a 3.3kW/80kWh device. The researchers should design a package enclosure that minimizes footprint, maximizes ease of installation and

maintenance access, and provides secondary safety containment. They should determine maximum current density. Chemistry characteristics should be evaluated for windows of pH and other factors such as dissolved oxygen that might lead to precipitates that could mask the cathode's performance. The researchers should develop a simple test kit and procedures for ensuring the chemistry stays within these windows.

2.22.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary public benefit of this technology to California ratepayers would be from increased reliability of the California electric system. Reliability benefits would accrue from reduced impact of power outages, improved power security, and shorter response times. During power outages the technology could extend substation control power for up to four days rather than a few hours. This could improve response times for re-energizing the grid and restoring customer power.

At this time utilities use lead acid batteries in substations. With careful maintenance those batteries have an average life span of 15 years. It costs $2,000/year/battery system to service lead acid substation batteries in an effort to maintain adequate reliability. This is based on a minimal one hour monthly inspection and an eight hour quarterly maintenance schedule at $50/hour. The 15 year cost of a new lead acid battery system is $65,000. The researchers estimated the zinc chloride flow battery would have a 15 year cost of $10,250. This estimate could go higher if safety codes for chlorine tanks require more frequent inspections.

Other applications for the zinc chloride flow battery include telephone cell towers and server farms that require on site power backup. These applications could greatly expand both the potential market and the public benefits.

2.22.8 Overall Technology Transition Assessment

As the basis for this assessment the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.22.8.1 Marketing/Connection to the Market

PG&E expressed interest in partnering with the researchers to commercialize this product and could provide a significant market. PG&E identified a substation for the next step demonstration. The results of that test should be widely published to spur commercial acceptance.

2.22.8.2 Engineering/Technical

The researchers planned to build a 43 cell unit to meet the site specific voltage requirements of a utility application.

2.22.8.3 Legal/Contractual

The researchers filed Patent application #288.1001.01.

2.22.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

The onsite storage of chlorine poses safety risks. Common safety and maintenance procedures should be investigated and applied to the design and operation of the EnergyCell™. The researchers should develop strict quality assurance plans for manufacture, installation, maintenance, and operation to ensure that early failures do not cause early adopters to drop the product.

2.22.8.5 Production Readiness/Commercialization

The product is ready for field demonstration. The researchers should develop a commercialization partner.

2.23 A Building Integrated Relief Damper to Improve Comfort with Evaporative Cooling

Awardee: Steven Winter Associates

Principal Investigators: Marc Zuluaga

2.23.1 Abstract

Although evaporative cooling is not a new technology, it has failed to gain widespread residential use because most installations require homeowners to open windows to direct space cooling throughout the home. Some builders install an automatic ceiling damper that allows room air to pass through the attic area and out through the roof vents. The most popular brand of these ducts is called Up-Dux™. When the evaporative cooler comes on, air pressure automatically opens these barometric dampers, and when the cooler shuts off the dampers automatically close. However these ceiling dampers rely on gravity to close the damper. Often the dampers do not close completely, resulting in significant leakage and an energy loss during the winter. The researchers in this project improved upon the barometric damper concept by incorporating a passive wax filled heat piston to ensure that the vent is more tightly sealed, reducing energy loss. The Building Integrated Relief Damper (BIRD) was designed to open the damper when attic temperatures exceeded 90°F and close it when temperatures dropped below 80°F.

Keywords: Evaporative cooling, non-compressive cooling, thermal comfort, peak load reduction, pressure relief, pressure relief damper

2.23.2 Introduction

Evaporative cooling has been used throughout the world for thousands of years and has remained largely unchanged in configuration since patents were first sought in the United States for the technology at the turn of the twentieth century.[44] Although the most common evaporative coolers are designed based on patents obtained in 1945, this technology has yet to become widespread in residential applications largely because it cannot as effectively and automatically deliver conditioned air to every room in a house as compressive air conditioning can. In most cases evaporative cooling relies upon the active participation of the home occupant to open windows or doors to direct air flow from the cooler to rooms needing space conditioning.

Although cooling is also distributed throughout the home as air escapes through cracks in the building envelope, Title 24 standards to improve the building envelope have lessened the contribution of this type of exhausting system. To compensate for the loss of this passive exhaust system and to eliminate the need to open windows, Up-Dux™ brand ceiling dampers were introduced in the late 1980s. These dampers are installed in the ceiling, venting to the attic using a gravity relief system to open the vent when the home is pressurized as a result of evaporative cooler usage. With the introduction of these dampers, the evaporative cooling system became much more automated. However, because the gravity relief system does not seal tightly, the dampers introduce significant heating loss when the cooler is not in use. Consequently homeowners typically winterize the vents with magnetic covers.

The researchers in this project sought to improve on the damper concept by reducing the heating energy penalty during the winter. The Building Integrated Relief Damper (BIRD) has a similar form factor to Up-Dux™ dampers. However, a passive wax filled heat piston is used to open and close the damper based on ambient conditions within the attic as shown in Figures 26 and 27. The heat piston mechanism is an off the shelf HVAC component that relies on the expansion and contraction of wax to activate the piston at various temperatures. The researchers selected a piston that would open the duct when attic temperatures exceed 90 ^{o}F and close it when temperatures drop below 80 ^{o}F.

The researchers performed bench testing on a prototype BIRD to quantify the performance in comparison with Up-Dux™ dampers (Figure 25). The prototype was refined into a second generation BIRD which focused on minimizing leakage through the vent during periods of non-use (Figure 26). The second generation BIRD was installed in two California residences for field evaluation. The retail price of the second generation prototype BIRD was estimated at $198, significantly higher than Up-Dux™ dampers which retail under $50. The researchers anticipate the cost could be lowered with higher volume purchasing and may be offset by utility

44 Wikipedia, 2009. Evaporative Cooler, June 7. http://en.wikipedia.org/wiki/Evaporative_cooler.

incentives. The researchers noted that additional market penetration would lead to a yearly source energy reduction of 54,000 MBTU for every 10,000 new houses that used evaporative cooling as an alternative to compressive cooling, indirectly suggesting that reduction in leakage would contribute to consumer acceptance.

Figure 25: First Generation Building Integrated Relief Damper Prototype

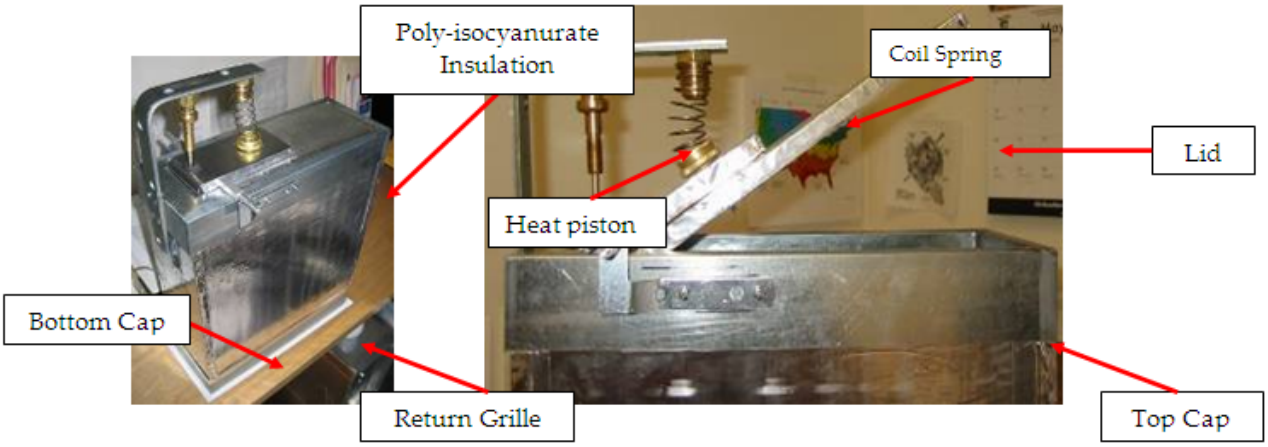
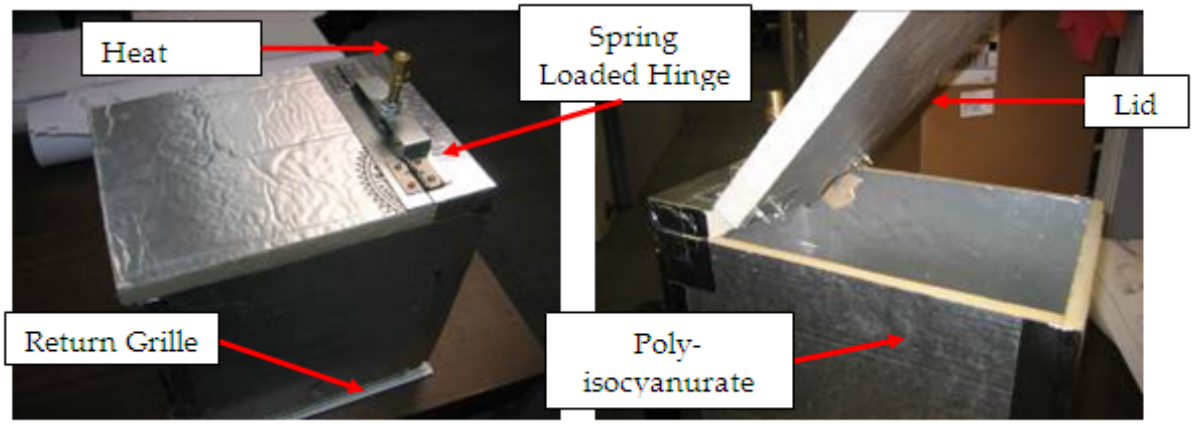


Figure 26: Second Generation Building Integrated Relief Damper Prototype



2.23.3 Objectives

The goal of this project was to demonstrate the feasibility of the high performance, low cost Building Integrated Relief Damper (BIRD) for improving air distribution effectiveness and comfort in houses with evaporative cooling. The researchers established the following project tasks and objectives:

1. Develop a first generation prototype BIRD that can be easily mounted in the ceiling of a house during new construction or as a retrofit and relieves 100 cubic feet per minute of indoor air when a house is pressurized to 10 Pa during evaporative cooling.
2. Assess the ease of installation of the first generation BIRD using a mock-up ceiling setup. Use bench top testing to quantify the airflow versus pressure drop characteristics of the relief dampers to evaluate Objective 1 airflow performance objectives.
3. Assess ease of installation in a retrofit house application. Quantify the airflow distribution benefits associated with BIRD during evaporative cooler operation in a house. Evaluate house temperature distribution during evaporative cooling before and after the installation of BIRD.
4. Demonstrate a second generation BIRD design that will allow less than 2 cubic feet per minute of house air to escape during times when an evaporative cooler is not operating (when house pressure is 4 Pa) and has an R value of 7 $ft^2h°F/Btu$ when sealed.
5. Demonstrate that BIRDs can maintain a 3°F difference in space temperature throughout a house during evaporative cooling based on field laboratory results.
6. Confirm that the projected retail price of $50 per damper is feasible based on project findings.
7. Identify the optimal configuration of dampers for typical California one and two story home plans based on performance testing and cost analysis.

2.23.4 Outcomes

1. Researchers mounted the first generation BIRD in a prototype house and found it relieved 90 cubic feet per minute of indoor air at a pressure of 10 Pa.
2. The researchers evaluated airflow performance in the prototype house using several design modifications relating to the return grill, fire damper, piston arrangement, and lid angle. Once the design was finalized, airflow measurements between BIRD and Up-DuxTM damper were compared at varying ambient pressures.
3. The researchers installed BIRD in the central hall of a 2,150 square foot home in Fair Oaks, CA, which already had four Up-DuxTM dampers installed in the living room and three bedrooms. The Up-DuxTM dampers were left in place and were not covered during the evaluation period. Additionally, the homeowner reportedly left a sliding glass door cracked open during the testing. Field measurements at this house indicated that the house operated at a pressure of 5 Pa when the evaporative cooler was operating. The researchers did not perform airflow measurements through the BIRD during the field test, but rather inferred them from bench test results (Objective 2) to determine that the one BIRD and four existing Up-DuxTM dampers relieved approximately 50 cubic feet per minute each for a total of 250 cubic feet per minute of the 1400 cubic feet per minute supplied by the cooler. The remaining 1150 cubic feet per minute was relieved through the cracked door and exfiltration in the building envelope. Temperature measurements within the areas where Up-DuxTM were installed indicated the

temperature variations in the rooms were within a 3 °F range. The researchers did not report temperature measurements in the room with BIRD.

4. The second generation BIRD achieved significantly more air flow than Up-DuxTM at house pressures less than 11 Pa and was measured at 13 cubic feet per minute. The insulated second generation BIRD had an R value of 7 ft2hoF/Btu through the lid. The design relies on good contact with attic insulation around the sides.

5. Results of bench test airflow measurements performed for Objective 4 (bench test of second generation BIRD) were extracted to determine the airflow in the California residence would have been 160 cubic feet per minute at 5 Pa. The researchers concluded the higher airflow of the second generation prototype would improve performance over the first generation prototype and would consequently maintain less than a 3° temperature difference throughout the home. No actual field work or experimentation was conducted as part of this task.

6. The researchers estimated retail price of the second generation BIRD to be $198.04. They opined this cost could be reduced by approximately 25 percent through volume, standardization, and energy efficiency incentives. Because BIRD allowed for 220 percent more airflow than the 100 cubic feet per minute objective, the researchers suggested additional savings may be realized by using fewer BIRDs. This statement appears to be based only on the airflow needed and not to consider the comfort needs that might inspire users to install the devices in rooms to attract airflow.

7. Based on exfiltration through the building envelope and four to five BIRDs, the researchers identified potential locations for a single story Northern California prototype home and a two story Southern California prototype home. They suggested some additional products to overcome air management problems, such as closing of bedroom doors. They performed no testing or analyses to evaluate the optimality of the device locations suggested.

2.23.5 Conclusions

1. BIRD was easily installed. However the first generation BIRD measured 90 cubic feet per minute pressure relief. The Up-Dux™ damper used for comparison relieved 200 cubic feet per minute using the same ambient air pressure. A second generation prototype exhibited performance more similar to the Up-Dux™ pressure relief at 10 Pa.

2. The researchers met the objective to fabricate and to bench test the first generation prototype design. The report did not provide many details of the experimental setup, controls, or instrumentation/calibration, and it did not include an error analysis. However, the design of the test chamber appeared to be effective in isolating the airflow contributions of each duct configuration.

3. The researchers failed to meet the objective to evaluate the first generation BIRD in a field setting. The lack of benchmark testing prior to installation of BIRD prohibited the researchers from performing a cost-benefit analysis for the proposed technology. Further, because Up-Dux™ dampers were left in place and the house doors were not

closed, testing conditions were inadequate to isolate contributions of BIRD to the system as a whole. The researchers' test design was not described, so the rationale for including temperature measurements in rooms with Up-Dux™ was not clear. Once again test instrumentation, calibration data, and error analyses were not included in the report. The researchers proposed to test airflow resulting from BIRD using balometer measurements, presumably during this field test. Airflow data stated as a part of this task was the result of bench testing performed during Objective Task 2. Performance of BIRD and Up-Dux™ were assumed based on the bench top testing, rendering the outcomes somewhat speculative. Because the field testing was done with a mixture of Up-Dux™ and BIRDs, large scale field testing for airflow resulting from BIRDs would have been impossible. The researchers stated the second generation BIRD relieved approximately three times the airflow of Up-Dux™, but this statement is similarly based on bench test data rather than actual field testing. It is important to note the researchers reported the lid angle of BIRD during field testing differed from the lid angle observed during bench top testing, and lid angle appears to be quite important to BIRD performance. The analyses and conclusions relative to Objective 3 are not convincing.

4. The researchers met some of the performance objectives for the second generation BIRD. Whereas the first generation prototype failed to meet airflow objectives, the second generation prototype not only met the objectives, but exceeded airflow performance and proved more consistent over most of the pressure range than Up-Dux™. The gravity mechanism employed by Up-Dux™ significantly restricted airflow at low pressures when the lid was at very low angles. BIRD maintained a more consistent airflow as a result of a near constant 30° lid angle. Leakage goals were not met for non-operational periods, with a leakage of 13 cubic feet per minute compared to a goal of 2 cubic feet per minute. However, the researchers did not perform any design iteration to achieve this goal. Because the first generation prototype came much closer to the goal, with leakage measured at 3.5 cubic feet per minute at 4 Pa, there was significant untapped potential for reduction in leakage. The researchers stated the goal of 2 cubic feet per minute was ambitious, but without focused design iteration and testing, this conclusion was premature. The insulating performance objective was met, with the assumption that attic insulation was in good contact with the sides of BIRD.

5. The researchers did not demonstrate the second generation prototype could maintain a 3 °F temperature difference throughout the house. Because the researchers did not install or test the second generation model in a controlled field environment as proposed, their conclusions were based on hypotheses rather than demonstrations. Testing performed as part of Objective 2 (field demonstration of first generation prototype) was conducted in an uncontrolled environment and should not have been the basis for performance extrapolation. The better airflow demonstrated in Objective 4 (bench test of second generation prototype) should have led to more constant temperatures, but this was not demonstrated in the field using the second generation prototype.

6. The researchers did not meet the objective to confirm a $50 retail price per BIRD. This performance objective was reasonable and appropriate, as it was likely drawn from the actual retail cost of the alternative, Up-Dux™. Incentives are available to offset the costs

of the dampers. However these incentives would likely be available to Up-Dux™ installations as well. The researchers did not perform adequate benchmark testing between the two systems to determine if the benefits gained from the improved technology exceeded incremental costs between the Up-Dux™ and BIRD dampers.

7. The researchers provided a potential set of locations for dampers in one and two story home floor plans. It is not clear they met the objective to identify the optimal configuration of dampers for typical California one and two story home plans as there were no analyses or tests to confirm the optimality of their proposed locations.

2.23.6 Recommendations

The researchers proposed an alternative to Up-Dux™ brand dampers by integrating a heat activated wax filled piston that would reduce heat loss during periods of non-use. Because the technology was proposed as an alternative to Up-Dux™, it is logical for cost and performance of BIRD to be directly compared to that of Up-Dux™. If costs are not comparable, benefits must be greater for consumers to embrace the technology. The researchers determined that BIRD would have a retail price four times that of an Up-Dux™ damper. Therefore performance benefits must outweigh the costs. The most obvious benefits could include the following:

- Increased airflow leading to increased temperature stability and comfort.
- Decreased leakage leading to decreased energy consumption during the winter.

If either of the benefits above is significant enough, it could lead to a greater market share for evaporative cooling as an alternative to compressive cooling, which would in turn lead to additional cost savings and environmental benefits.

Although BIRD exceeded the airflow objective by 220 percent, this is not an appropriate comparison. Rather, it should be compared to Up-Dux™ airflow, resulting in only a 10 percent improvement over current technology. Given the number of tests performed, the airflow properties appeared to be similar, at least at the upper end of air pressures. BIRD did show a significant decrease in non-use period leakage, with only 33 percent of the leakage demonstrated by Up-Dux™, with potential for much more reduction based on first generation prototype testing. The airflow improvement alone does not appear to justify replacement of Up-Dux™ with BIRDs and does not seem significant enough to lead to a larger market share of evaporative cooling as an alternative to compressive cooling. However the large reduction in leakage could lead to considerable savings during winter months. The researchers neither noted this cost savings potential nor quantified it. Without this analysis it is unclear that the technology would lead to additional market penetration of evaporative cooling in 10,000 homes per year.

As part of continued development of this technology, the Program Administrator recommends the following tasks be completed:

1. Conduct field testing of the second generation prototype in a retrofit house containing four to five BIRDs in a similar configuration as identified during Objective 7 and compare results to benchmark testing of Up-Dux™ in the house prior to the retrofit.
2. Evaluate the potential to automate operation of the evaporative cooler fan with the automated opening of the BIRD.
3. Quantify the cost savings from heat loss reduction when comparing Up-Dux™ to BIRD dampers.
4. Perform a life cycle analysis for the BIRD in comparison to the Up-Dux™ damper.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.23.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. The researchers estimated improvements in relief dampers would lead to 10 percent increase in market share for evaporative cooling in new homes as an alternative to compressive cooling. This translates to approximately 10,000 new homes each year. Should this market penetration be realized, California would receive the following yearly energy savings:

- Site energy reduction of 5000 MWh
- Source energy reduction of 54,000 MBTU
- Peak electric demand reduction of 30 MW

The benefit analysis presented by the researchers applied only to new house construction. Retrofit potential was not evaluated nor were non-residential applications. Although it is unclear that the improvements in the BIRD damper system over the Up-Dux™ are significant enough to result in such an increase in new house or retrofit market share, the BIRD damper does offer significant potential to reduce energy loss through non-use period leakage. This

potential was not quantified. The researchers' benefit calculations also assume that evaporative cooling would be employed as an alternative to compressive air. However evaporative cooling may not entirely negate the use of compressive air cooling, particularly in monsoonal climates or coastal regions which have humidity too high to allow evaporative cooling to perform effectively.

2.23.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.23.8.1 Marketing/Connection to the Market

The researchers had not performed market research and analysis. However the target market is residential houses. This technology should not be limited to the residential sector, and would have applicability in nearly any setting in which evaporative cooling is used. BIRDs are proposed as an alternative to widely available Up-Dux™, which have a strong market connection and distribution path that could be leveraged in a competitive environment. A retrofit market would also seem to exist.

2.23.8.2 Engineering/Technical

The researchers planned to continue development of the technology towards commercialization and have not encountered any engineering or technical obstacles.

2.23.8.3 Legal/Contractual

The researchers had not performed a patent search to identify any potential infringements.

2.23.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

Because of technology immaturity, these plans had not been developed.

2.23.8.5 Production Readiness/Commercialization

The researchers had not identified a commercialization partner. They will not be able to pursue commercialization without a partner.